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**Committee on the Peaceful Uses of Outer Space**

# Report on the second United Nations International Conference on Spin-off Benefits of Space Technology: Challenges and Opportunities

**(Tampa, Florida, United States of America, 30 March-3 April 1998)**

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# I. Introduction

## A. Background and objectives

1. The General Assembly, in its resolution 43/56 of 6 December 1988, requested the Committee on the Peaceful Uses of Outer Space to consider at its thirty-second session a new agenda item entitled "Spin-off benefits of space technology: review of current status". Pursuant to its work, the Committee, starting in 1992, recommended that the United Nations Programme on Space Applications should consider devoting at least one of its training courses, seminars or expert meetings each year to the promotion of spin-off benefits from space. Organized as part of the 1998 activities of the Programme, the second United Nations International Conference on Spin-off Benefits of Space Technology: Challenges and Opportunities was a response to that mandate.

2. The General Assembly, in its resolution 52/56 of 10 December 1997, endorsed the activities of the Programme on Space Applications for 1998, including the organization of the above-mentioned Conference.

3. The main objectives of the Conference were: (a) to expose industrialists and private establishments in the developing countries to the many ways in which their companies and countries could directly and indirectly benefit from the various technologies that have and are being developed for space exploration and utilization; (b) to accumulate experiences by developed and developing countries in the application of space technology spin-offs; (c) to identify a common approach to cooperation among interested industrial partners in both industrialized and developing countries; and (d) to discuss joint follow-up activities for strengthening the technological capabilities of developing countries in order to realize the spin-off benefits of space technology.

4. The present report covering the background, objectives, organization and recommendations of the Conference has been prepared for the Committee on the Peaceful Uses of Outer Space. Participants will report to the appropriate authorities in their own countries.

## B. Participants

5. The United Nations targeted for participation in the Conference individuals in decision-making positions in governmental agencies and private industries who were engaged in programmes and projects in which spin-offs of space technology were being or could be utilized. The co-sponsors also requested that each participating entity or private establishment wishing to attend the Conference should send both its chief executive officer and senior technical manager.

6. Funds allocated by the United Nations, the Federal Laboratory Consortium of the United States of America, the International Society for Photogrammetry and Remote Sensing and private entities in the United States, including Lockheed Martin Corporation and Spectrum Astro Inc., were used to cover international air travel and per diem expenses for the period of the Conference for the senior technical managers from selected organizations and companies from developing countries.

7. The following Member States, United Nations Secretariat units, governmental and non-governmental organizations, international organizations, and private entities were represented at the Conference: Brazil, Bulgaria, Canada, Chile, China, Egypt, Ethiopia, Hungary, India, Japan, Kenya, Nigeria, Romania, Tunisia, Thailand, United States and Zambia; Office for Outer Space Affairs of the Secretariat; Canada Centre for Remote Sensing, Federal Laboratory Consortium (FLC), United States Department of Commerce, United States Department of Energy and United States National Aeronautics and Space Administration (NASA); International Society for Photogrammetry and Remote Sensing; Farabow, Finnegan, Garett & Dunner L.L.P., Henderson, HOBECO Ltda., Lockheed Martin Corporation, Mitsubishi Electric Corporation, Nippon Electric Company, OPTOMECH Engineers PVT, Ltd., ORBIMAGE, Resource 21, Space Imaging-Earth Observation Satellite Company (EOSAT), Space Vest, Spectrum Astro Inc. and Système pour l'observation de la Terre (SPOT)-Image. Speakers and chairmen of the Conference came from Brazil, Chile, Canada, India, Japan, United States and the Office for Outer Space Affairs.

# II. Observations and recommendations

8. Throughout the Conference, participants had the opportunity to take part in discussions on spin-off benefits. Within the framework of the specific themes of the Conference, discussions were held on the following issues: participation of potential business partners in developing a joint business plan, including the needs and desires of partners; emerging opportunities available to all participants, including projects that are appealing to developed countries and that could provide significant benefits to developing countries; and steps to be taken by developing

countries to further their development, with emphasis on challenges and opportunities in spin-off programmes. The following observations and recommendations were made:

(a) The successful transfer of space-related technologies and spin-offs from research and development institutions to industry required the availability of appropriate methods and infrastructures, as well as clearly defined government policies and support. Those requirements included the following: establishment of organizational structures dedicated to technology transfer and commercialization in national space agencies or other government bodies in charge of technological development; stimulation of marketing mechanisms focusing on widespread promotion of technologies and spin-offs; development of financial incentives encouraging innovators, entrepreneurs and investors; creation of relevant educational and training networks;

(b) Of paramount importance was the elaboration of a sound business plan in a manner capable of attracting interested investors by focusing on the value of products and services to be offered to the public. In creating a friendly investment atmosphere, investment opportunities were vital for the development and success of technology transfer projects. In order to attract the latter, the following factors were emphasized: political will and commitment by national leaders regarding the introduction of new technologies and development of appropriate infrastructure; political, social and economic stability to enhance the possibilities of foreign investment in emerging markets; and tax incentives to encourage both foreign and local investors. The latter were instrumental in order to stimulate the adaptation of technologies required from abroad to meet local needs. It was suggested that Governments could provide subsidies and financing on a liberal and competitive basis to promote opportunities in research and development, as well as funding and facilities to encourage and facilitate technology transfer. Finally, effective and close coordination between Government and industry was absolutely necessary to further development programmes in the area of space technology spin-offs and, generally, to achieve basic sustainable development programmes;

(c) Networking facilitated technical development opportunities in the establishment of contacts with Government, industry, academia, financial organizations and others. With regard to obtaining the support of developed countries, contacts should be established with the focal point at the local level. Direct contacts between industry leaders would also facilitate partnerships and collaborative ventures;

(d) International cooperation was considered to be a powerful mechanism in promoting the development and application of high-technology spin-offs in a developing country. That mechanism needed to take into account the policies of developing countries regarding space technology and the priorities and policies of the international organizations assisting developing countries in strengthening their technological capacities;

(e) Another significant aspect in meeting the challenges of international cooperation was the establishment and maintenance of contacts with potential facilitating organizations from around the world, including national and regional space institutions such as those represented at the Conference. When an opportunity for a cooperative venture arose, it should be encouraged and taken. Also of importance was the substantive involvement of the private sector as much as possible in those projects in order to ensure their sustainability. Moreover, business leaders needed to talk to government representatives to state their interests as well as using other methods to express their views, including contact with chambers of commerce. Information generated from the Conference should be passed on by the participants to relevant and supportive government agencies in order to facilitate follow-up;

(f) Regarding the challenge of the development of human resources, technology transfer from spacefaring countries to developing countries could be promoted by providing more training opportunities for scientists and engineers of developing countries. Furthermore, those opportunities would be instrumental in understanding the direction of development in civil space technology, which would facilitate the decision-making process in developing countries, particularly in prioritizing the space-related research and development activities to be pursued. The solid foundation for future entrepreneurs and innovators in basic education was of particular importance, especially in relation to applied research and technology transfer and its adaptation. That challenge would permit local entrepreneurs and industries to prepare themselves to begin development activities by acquiring licences to technology and by training in the effective utilization of know-how and the effective management of a high-technology-based business;

(g) Technology transfer was a two-way process. It was important that when contacts were made between a potential provider and user, both parties should benefit

from the transaction. Large companies might not necessarily be the best contact for research and experimental institutions when seeking potential partners in specific transactions. It might therefore be more appropriate to approach small to medium-sized firms. However, a potential problem in that approach was that such firms did not necessarily have available the resources needed to establish business contacts with industry counterparts, for example, in connection with industry trade shows;

(h) Companies from developing countries involved in the field of space technology required certain preconditions in order to proceed with space research as a tool for the development of advanced technology. The preconditions included: an existing level of experience and education in order to absorb new knowledge; the organization of existing groups and institutions in a way that enabled the smooth flow of relevant information; close collaboration between research groups in order to produce the best results; international cooperation; and, in particular, cooperation with more experienced partners in order to successfully transfer technology and subsidies from Government or other sources;

(i) Regarding the role of the United Nations, the Organization could play a vital role as a facilitator. The Office for Outer Space Affairs should continue to assist developing countries and pursue the issues of technology development at the local level through international conferences such as that covered by the present report, which provided a good forum, and by promoting interaction between developed and developing countries in technology applications. The organization of a third international conference on spin-off benefits of space exploration and implementation of follow-up activities was suggested. At the third conference or perhaps through the World Wide Web site discussed in subparagraph (j) below, representatives of developing countries could identify the needs or specific problems of each of their countries, thereby giving an opportunity to the developed countries to better understand how space-derived technologies could be better applied towards solving those problems. Other potential roles for the United Nations included the identification of companies that had received spin-off technology from the space laboratories of spacefaring States, an assessment of the capabilities of those companies and a study of the extent to which they were interested in participating in the transfer of their know-how to other companies in developing countries;

(j) The Office, in collaboration with interested industries, should develop a Web site, available through the Internet, that could be accessed by all developing countries for information on all aspects of space technology transfer. The Web site could contain information for industries on opportunities for partnerships, and provide a link-up to a database of usable technologies that any country could access and use. The Web site should not only cover technology transfer successes, but also refer to the failures experienced by developed countries when implementing the new technologies.

9. Taking into account the importance of adequate access to space technologies and applications relevant to sustainable development programmes in developing countries, including the mutual commercial benefits available to both providers of technology and its recipients and users, international cooperation in the area of space technology transfer and spin-offs should attract the particular attention of the Member States. In that connection, the legal frameworks and international agreements developed by United Nations bodies and agencies had been essential to fostering international cooperation in programmes for the transfer of space technology.

10. On the eve of the twenty-first century, space cooperation with developing countries had become a key issue. Space industries from developed countries wishing to do business in developing countries needed to harmonize their policy and business strategies within the framework of national space policy, usually defined by a national space agency and by the political decision-making bodies of the developing country that had decided to use space technology for the development of the national economy.

11. All participants expressed the opinion that the general organization of the Conference and the planning of the presentations were of high quality. Participants were of the view that developing countries had become better able to obtain precise knowledge about the importance of investing in space applications programmes in order to take advantage of their benefits in improving the conditions of life in their respective countries. They also expressed their appreciation to the United Nations for having organized the Conference and to the Governments

and industries represented for making an invaluable contribution to its success.

# III. Presentations and discussions during the Conference

## A. Background

12. The global political, economic and technological changes of the past decade had altered the operating environment of the space industry. Space technology had become an economic asset and a valuable source of know-how, technology transfer and spin-off programmes, rather than a means of political supremacy. Space activities incorporated important areas of high technology, including computer software and hardware development, sophisticated electronics, telecommunications, satellite manufacturing, life sciences and launch technology. Space activities also involved significant issues of international trade and policy, such as global markets, gaining access to remote areas, government-subsidized competition and international standardization and regulation. Cooperation was the key to maximizing spin-off benefits and providing mutual advantage through the promotion of joint activities between developed and developing countries.

13. Through services and products directly and indirectly derived from space technology applications, the quality of life had been enhanced particularly in the areas of distance education, training and development, solar energy, fisheries operation, telecommunications, health and telemedicine, precision agriculture and crop yield assessment, global monitoring of natural resources and the environment.

## B. Spin-off benefits of space technology to developing countries

### 1. Telemedicine and human health

14. The provision of health services to non-urban and isolated areas had always been a challenge for developing countries. The health and safety of many countries could be significantly improved with proper planning of natural resources, water supply and sanitation. In addition to the impact of space activities on business and daily life, there were numerous socio-economic benefits that derived directly from scientific and space exploration missions. As a result of improved technology, telemedicine was becoming increasingly cost-effective. Given the growing financial constraints of today in most sectors, including the health-care industry, alternative methods of delivering health care were being sought.

15. For nearly 30 years, NASA had established a bridge between space technology benefits and research in the medical field. A number of applications derived from space technology had influenced areas such as biomedical instrumentation, cardiology, surgery and medical imagery. In 1989, NASA established a space bridge to Armenia five months after the earthquake in the region. The system was a double satellite hop using the American Telephone & Telegraph (AT&T), International Telecommunications Satellite Organization (INTELSAT) and NASA Satcom satellites. It consisted of a two-way audio channel and one-way black and white video link. Once established, the system was used easily to alleviate the effects of other disasters in the region.

16. NASA had also been applying remote sensing technology, specifically satellite and airborne Earth sensing, to study various environmental and public-health-related problems around the world. The data acquired was applied to the regulation and monitoring of Earth resources and the environment. Improved environmental conditions led to an improved quality of life for the population. Such an approach made it possible to study habitats that harboured vectors capable of transmitting diseases from one species to another. Since certain diseases were associated with particular landscapes and environmental conditions, the study of those associations could provide research tools capable of identifying the time and place of future global outbreaks of human diseases.

17. An example of applying remote sensing technology to improve public health was provided by Indonesia, where there were high levels of malaria and tuberculosis in various regions of the country. The Government of Indonesia, through its National Development Planning Board, funded the Agency for Assessment and Application of Technology to study the problem and make recommendations on the reporting of disease statistics. In order to report the data from two regions where the diseases were prevalent, it was decided to automate the process in a very user-friendly manner by developing a personal-computer-based geographic information system (GIS) that used the exact reporting format of the clinics. The process made it easier to fill out the forms digitally. In order to assess the spatial distribution of people with the disease in association with the potential disease vector habitats, the following types of spatial information were entered into the system: political boundaries, clinic locations, patient

living locations, soil types, topography, land use and cover. Land Remote Sensing Satellite data were used to create detailed land-cover maps. The data sets were currently being statistically assessed.

18. With better information at the national level, governmental agencies could also better plan and prioritize the use of limited resources to help solve serious health problems at the local level. The overall goal of the project in Indonesia was to develop a user-friendly methodology that could be implemented in local clinics to better study, report and solve health problems in local clinics across the country. An important aspect of the project was to emphasize the importance of using GIS on a daily basis providing government officials with an effective and operational system for monitoring diseases.

19. To facilitate the dialogue between physicians and the space industry, in early 1996 the European Space Agency (ESA) created an association called Promotion of Medical Use of Space, which disseminates information about space technology and ongoing projects with the space industry in order to promote the transfer of space technology to medical applications. ESA had invited physicians, medical research organizations, hospitals and the biomedical industry to become active members of the association, and thereby to interact with the space industry.

### 2. Agriculture

20. With the emergence of an agricultural information revolution, information derived from satellite remote sensing and aerial photography had made it possible for farmers and agribusiness companies to estimate food and fibre production and to develop survey sampling frames and prediction models. The data could be used in agricultural surveys to accurately predict crop yields, to estimate and map crop damage, to monitor conservation practices and to implement precision farming practices.

21. Farmers were beginning to rely on remote sensing for timely crop monitoring and information on production in large disparate areas. Such information was used to identify crop health problems, monitor food supplies and assess famine risk. Remote sensing offered numerous benefits in the field of agriculture, in particular the following application opportunities: (a) early identification of crop health problems, which would allow growers to employ timely remediation techniques; (b) targeted remediation of crop problems resulting in lower costs and reduced environmental impacts; (c) simultaneous monitoring and management of large disparate areas with little additional cost or effort; (d) early crop yield predictions and periodic revisions throughout the growing season with improved accuracy; and (e) the analysis of overall crop, field and farm performance to evaluate sensitivity to management changes and achieve production optimization.

22. In addition, the analysis of satellite and ground data in conjunction could produce acreage data with substantially more statistical precision at local levels. Earth observation and weather satellite data could also be analysed together to aid in monitoring crop conditions. Furthermore, the monitoring of vegetation conditions on a national scale could be carried out through the use of data generated from polar-orbiting weather satellites.

### 3. Data imaging applications

23. In the field of high-resolution imaging, countries were able to access a wide range of products that had many useful applications. NASA technologies were being used to help map, plan and improve country development programmes. High-resolution topographical maps could also be used in commercial applications ranging from road-building and urban planning to community development and identification of flood plains.

24. To assist in the advance planning of relief efforts, vegetation monitoring information was used to assess regional food and water supplies and to mitigate the risks of drought, pest infestation and environmental contamination. Geospatial technology was used to assess food-supply vulnerability in drought-stricken areas. For instance, African countries continually faced food shortages that resulted in widespread famine and starvation, devastating the population. The normalized difference vegetation index was used to measure key variations in agricultural productivity. The results of those measurements compared to long-term averages and correlated with rainfall, market prices and logistical factors determined the spatial distribution of the food-security risk.

25. In terms of global security, high-resolution imaging and data applications could be used to monitor regional conflicts. More importantly, in the field of peacekeeping, the images and data could be made available to countries and individuals around the world in a timely, accurate and cost-effective manner.

26. Regarding fisheries management, remote sensing images had revealed important patterns in both the sea-surface temperature and pigment concentration. The distribution and relative abundance of fisheries resources

were related to surface oceanographic conditions. The process of using remote sensing data allowed oceanographic information to be provided to vessels, and vessel operation data sent back to shore enhanced both the industry and resources management. The data acquisition allowed fishermen to obtain information about surface temperature distribution and to reduce operation risks and costs by searching only in areas with a high probability of success. The same data allowed managers to track current fish-population conditions, to carry out faster resource analysis and to provide fleets with operational recommendations. The information acquired was useful in optimizing the sustainable exploitation of natural resources and in managing the existing fishing infrastructure in the most cost-effective manner possible. The Food and Agricultural Organization of the United Nations also assisted numerous developing countries, such as China, Costa Rica, Thailand and Viet Nam, in the sustainable development of fisheries operations. That process benefited villages by enhancing their food supply and income and through the overall improvement of their quality of life.

## C. Research and development

27. Space technology provided know-how, as well as knowledge of who and what was involved and why, from a valuable bank that was used by companies worldwide to bring new products, processes and services to the world market at more competitive prices. The indirect effects of space technology applications, previously considered by-products of research and development, were increasingly seen as a meaningful element of industrial policy. To remain competitive in their fields, the non-space industrial sectors were more demanding of the new technology, processes and materials.

28. The most active players involved in the transfer of space technology were Governments, space agencies, multisectoral consortia, aerospace companies, small and medium-scale enterprises, research laboratories, academic centres and networks consisting of different organizations ranging from large companies to research laboratories and non-space industries. Technology transfer and spin-off programmes developed by national and international space agencies demonstrated a new market-oriented approach based on demand and well-identified market segments. Space technology provided a reservoir of potential solutions for the industry.

### 1. Government role

29. The successful transfer of technology and spin-offs required an appropriate method and infrastructure, as well as a clearly defined government policy on each technology to be transferred. FLC promoted and strengthened technology transfer throughout the United States. In that capacity, FLC represented the technology outreach programmes of 16 federal departments and agencies operating over 600 national research and development laboratories. The mission of FLC was to cooperate with federal laboratories and the private sector in the following areas: (a) developing and administering technology transfer activities; (b) advising and assisting federal laboratories and industry in transferring technology; (c) providing a clearing house for requests at federal laboratories for technical assistance from States, local governments and industry; and (d) facilitating communication, coordination and resolution of federal technology transfer activities throughout the federal research and development community.

30. Mechanisms used for accessing the resources and expertise of FLC included the following network: (a) sharing of information; (b) exchanging personnel; (c) carrying out cooperative research and development agreements directly with private companies and other entities; (d) working cooperatively with NASA; and (e) forming consortia and using technology developed under government contracts.

31. In addition to the FLC network, six regional technology transfer centres had been established through a competitive process, designed to benefit a specific industry, using an innovative process model in high-technology development. Four of the six centres were managed by universities. Forty per cent of the activities of the network were related to technology and concepts developed by NASA. The concept was developed and commercialized, and appropriate market research was then done on the market viability of a product. When those steps were completed, a product was deemed appropriate for possible commercial ventures, and would be offered to the private sector for financing and ultimate distribution to the market.

32. For the private sector, the advantages of working with the United States federal laboratory system was that the laboratories had a reservoir of facilities and talented people with the ability to undertake long-term projects that

required more time and resources than what some private industries could provide.

33. Over the past 25 years, there had been a successful increase in and diversification of the technologies of NASA through commercialization. Research in aeronautics, in life, microgravity and space science, in communications and in space flight and access had brought an array of high technologies ready for transfer to the private sector. Interested developing countries might wish to work and cooperate with NASA on mutually beneficial projects. Many countries had already entered into cooperation agreements with NASA in fundamental science and technology areas. NASA was interested in cooperating with civil space programmes of particular countries where mutually acceptable benefits could be derived. To facilitate that process, the following steps were to be taken into account:

(a) An initial request should be made by an interested country wanting to cooperate with NASA;

(b) An exchange of teams from both sides would be made to discuss and to determine common areas of interest;

(c) Beneficial interests of both countries that did not conflict with their national policies on transfer of technology would be determined when mutual agreement was reached;

(d) NASA would act as a coordinator for the benefit of the interested country with all other agencies and departments of the United States Government.

34. In providing such opportunities to developing countries, the cooperation between NASA and a particular country would: strengthen the technological capabilities of the developing country; provide the opportunity to examine and adapt new technology to meet local needs; and expand market opportunities for space-related industry in the country concerned. Furthermore, a policy of creating reciprocal relationships where knowledge was shared through mutually beneficial cooperation was being offered by NASA through internships to foreign officials, so long as reciprocal opportunities were made also available to NASA officials.

35. In the area of renewable energy, the United States Department of Energy had undertaken extensive research into the production of energy through wind, solar thermal sources and photovoltaic cells, as well as into lasers and high-temperature superconductivity. A successful tool was photovoltaic conversion used to provide power to man-made satellites. NASA pioneered photovoltaic power and supported Department of Energy programmes to expand terrestrial applications. The NASA jet propulsion laboratory was primarily responsible for developing advanced photovoltaic technology. Photovoltaic conversion of energy could provide a viable alternative energy source to sites where no conventional energy source existed, such as remote automated weather stations, sea-based navigation buoys and forest stations in villages of developing countries.

36. Photovoltaic conversion technology had been introduced in many developing countries to promote the use of renewable energy sources as a viable, cost-effective and environmentally friendly way to provide necessary power generation. Solar panels were being used in several African countries and in Brazil to provide electrical power to homes in rural and remote areas, and high-capacity storage batteries were used for solar-power-generated electricity in rural and remote areas.

### 2. Industry role

37. Lockheed Martin Corporation was teaming with various investors in order to establish firms with traditional vendors to develop a variety of communications services from space. The emerging systems were targeted to a variety of users. Practically every country in the world currently benefited from a range of communications services through participation in international, regional or domestic satellite communications systems. Satellite communications technology was an established critical tool for social and economic development, while advances in technology continued to lower the costs of its utilization. Communications satellites were used for a wide variety of purposes, including rural and wireless communication, news and data dissemination, emergency communication, navigation, disaster warning, television and radio programme distribution, search and rescue operations, telemedicine and remote education.

38. The above-mentioned technology had created huge opportunities that could promote economic development. Moreover, those benefits were potentially accessible to all sections of society and could further the process of sustainable development. Lockheed Martin recently announced its involvement as partner with other companies in the development and launch of the SATPHONE mobile communication satellite system. The system would provide telecommunication services across western Asia, northern Africa, the Mediterranean basin and eastern

Europe. It would offer the following opportunities to those regions: the enhancement of existing terrestrial communications network; the provision of superior service and flexibility to millions of customers; and the possibility for participating companies and countries to develop and benefit from multiple communication services.

39. Spectrum Astro, a rapidly growing private company, was dedicated to the development and production of reliable, affordable and timely space products. The company was creating and addressing opportunities, through partnership, for industries in developed countries to expand in the emerging markets of developing countries. It was dedicated to the promotion of technological advances in the miniaturization of electronics, computer-aided design and the standardization of components. It was also providing services and products for all phases of the life cycle of the space system, including: system engineering and mission development for space systems; development and production of small spacecraft bus vehicles; space electronics and power management systems; high-performance data storage systems; and electrical ground support and ground control equipment. Spectrum Astro recently announced its involvement in supplying the power systems for the Ellipso system, a global communications satellite system.

## D. Industry experiences in developing countries

40. The challenges confronting developing countries, particularly in the areas of emerging markets, involved developing a better, faster and cheaper strategy for participation in the market that should include technology transfer and academic and entrepreneurship training. A national project that met national needs could also provide for the design and manufacture of low-cost, high-performance small satellites and related subsystems for sophisticated defence, science and selected commercial opportunities. If implemented correctly, the end result would be a sustaining business base that would be capable of competing in global markets.

41. The opportunities available in the global space industry for developing countries included the following areas: commercial remote sensing; wireless communication; access to space (commercial launches); and precision positioning and timing. Most developing countries were not engaged in the full range of space activities, but were rather focusing on space applications with operational and commercial potential for developing business opportunities in the countries concerned.

42. In developing countries, much work had been done on products that had been derived from work in their space-related institutions and organizations. In the field of solar power, solar panels were used in Botswana, Ghana, Kenya and South Africa to provide electrical power to homes in rural areas. Since a majority of the world population lived in rural and remote areas beyond national power grids, using solar energy provided a less expensive alternative.

43. In Brazil, in the 1980s, many government incentives were given to the private sector to start industries based on high technology. As Brazilian industry gained experience, the Brazilian National Institute for Space Research (INPE) sought opportunities to find suitable companies to manufacture solar panels and provided an environment in which an exchange of ideas between private companies and INPE could take place. That approach by INPE resulted in a private company manufacturing solar panels for INPE as well as working on the Brazil-China Earth Resources Satellite programme. Another company had also built space components and assemblies for the Brazilian space programme. Several small Brazilian companies were cooperating with other developing countries, especially in selling or buying images from Earth observation satellites. INPE continued to collaborate and work with Brazilian industry in the development of its space-based industry.

44. In Bulgaria, research work was undertaken by the Bulgarian Aerospace Agency on Neurolab-B, designed for use on board the Mir space station for the psychological and physiological examination of crews. A version of that system was also being developed for clinical environments on Earth. The Agency had also developed an ultraviolet (UV) indicator for personal use that determined the presence and intensity of UVA and UVB radiation. That device provided individuals with a clear indication of the intensity of the Sun, and therefore assisted in determining the maximum amount of exposure to the Sun under different circumstances.

45. The application of space technology in China had played an important role in solving problems relating to population, resources, the environment, disasters, communication, transportation and education. The economic and social benefits gained from space technology had accounted for 70 per cent of the gross income of China Aerospace Corporation. In addition, the space industry of

China provided direct services to the national economy and scientific research.

46. Since the 1980s, the space technology and research industry of China had implemented a policy of applying space technology to benefit other national industries. From space research-derived applications, over 20 per cent were usually incorporated into other industries. Some examples of spin-offs in China include the following benefits: a low-temperature thermal tube transducer; a new energy resource, a zinc-air cell, based on $H_2$-$O_2$; fuel cells used in satellites and large Zn-$O_2$ storage batteries; a photo-electronic diameter measurement system; and an elaborate industrial process control system.

47. Moreover, a land survey satellite, Ziyuan-1, jointly developed by China and Brazil, was to be launched in 1998. The satellite could play an important role in the survey, exploitation, use and management of resources and in the monitoring of agriculture, forestry, hydraulic power, geology, minerals, oceans and the environment.

48. In Hungary, the National Crop Monitoring Operational Project was successfully concluded, and provided accurate crop yield maps 2 to 12 weeks earlier than the target date. The forecast yield data of the monitored areas were reported regularly to the Ministry of Agriculture.

49. India provided another example of government/industry cooperation in developing countries. In terms of technology transfer arrangements, the Indian Space Research Organization (ISRO) worked closely with industry in all facets of development of space-derived products and services. There was continuous interaction between companies and ISRO to ensure that proper quality-control procedures, inspection standards and other manufacturing requirements were followed.

50. Their collaboration included spin-off products that had been marketed under various trade names and that included optical and optoelectronic products for remote sensing data interpretation. As a result of their collaboration, private industry could develop on its own a series of products that used optics for industrial and medical imaging applications. The effective participation of a private Indian company, Optomech Engineers PVT. Ltd., in all stages of development of low-cost optical products for visual interpretation of satellite remote sensing data led to the granting of a licence to the company to market a series of optics-based products for industrial and medical imaging applications. As a result, several products had been successfully marketed by the company, and it had been able to expand into areas of medical imaging equipment and machine-tool manufacturing.

51. A review of the highly cooperative venture between Indian industry and ISRO resulted in the following observations and guidelines:

(a) Smaller companies run by technically qualified entrepreneurs were more likely to succeed in absorbing the technology faster;

(b) The licensor should identify a contact person in its organization with whom the licensee could communicate directly on all matters relating to technology transfer;

(c) The number of recipients of know-how for a technology or product should be in proportion to its perceived or estimated market potential;

(d) Technology transfer would enable the licensee to acquire skills that could be used for developing new products using the same technology but for different applications.

52. In Romania, particular attention was given to the development of a microsatellite mission for hazard management and monitoring of space communications, of global positioning and information systems and of Earth observation. In addition, Romania, through its National Institute for Aerospace Research and the Romanian Space Agency, had developed a small unmanned aircraft, a lenticular aerodyne, equipped to perform training in remote sensing communications, attitude control and navigation. The vehicle helped to reduce the period of time necessary to understand and adjust the phase of a mission, with lower costs.

## E. Intellectual property

53. Intellectual property concerns and related legal challenges involving technology in different countries required appropriate action in cases where a business held intellectual property. Identifying, protecting, transferring and preserving intellectual property raised issues of fundamental importance. Their various aspects involved such matters as the identification of intellectual property through an audit and protecting it in its different forms, including patents, trade marks and copyright. Protection of trade secrets, inventions and designs, computer software, trade marks and product configuration was needed in order to safeguard the rights inherent in the products. Confidentiality agreements were also necessary when applying for patent and trade-mark protection. Moreover, when com-

mercializing an invention, it must be ensured that the invention did not infringe on the patents owned by others, compliance with export control and foreign licensing regulations was therefore essential. Another area that required attention was technology licensing, which was important for a variety of reasons depending on business goals, market situations, the type of licensee, antitrust considerations and the type of intellectual property right. Licences could be structured as exclusive or non-exclusive and subject to limitations based on geography, field of use and/or time requirements, as well as renegotiation of the licensing provision.

## F. Human resource development

54. In order to be an efficient user of space technology and its spin-offs, companies in developing countries needed to acquire knowledge through a process of learning by innovation, whereby user/producer relations could play a instrumental role. Since the users of space applications technology in developing countries seemed to be playing a more active role in its promotion, development and use, there was a need for strategies that could provide users with a comprehensive knowledge of the technology. Such an approach would make it possible for users to establish a local production capacity, and would promote cooperation between users and producers.

55. Thus, specific education programmes should be elaborated to enable developing countries to become educated on the benefits of technology transfer and acquainted with the latest developments of space technology and its applications. Training courses were being implemented in space-related institutions to make their employees aware of the process of technology innovation and transfer. They were an essential factor in improving the infrastructure for business decisions and management, a matter of primary concern to both decision makers and policy makers.

56. Developing countries should also be aware of the resources available for training and education. For example, regional centres for space science and technology education were being established under the auspices of theOffice for Outer Space Affairs in various regions covered by the the regional economic commissions, including Asia and the Pacific, Latin America and the Caribbean, Africa and Western Asia.

57. As of April 1996, the regional Centre for Space Science and Technology Education in Asia and the Pacific, located in India, was offering unique opportunities for individuals to learn about space technology, including spin-off benefits, focusing on the themes of remote sensing, satellite meteorology, satellite communications, geopositioning systems and atmospheric science. The Centre for Space Science and Technology—in French Language was inaugurated in Morocco in October 1998, and the Centre for Space Science and Technology Education—in English Language was inaugurated in Nigeria in November 1998. The regional Centre for Space Science and Technology Education in Latin America and the Caribbean, to be hosted by Brazil and Mexico, was also to be inaugurated by the end of 1998. Following an evaluation mission in western Asia, a host country would beselected in the near future to host the centre in that region. Additionally, in central, eastern and south-eastern Europe, a network of space science and technology education institutions was being established.

## G. Exhibition

58. In conjunction with the second United Nations International Conference on the Spin-off Benefits of Space Technology: Challenges and Opportunities, an exhibition was organized at the Tampa Convention Centre by the 1998 Annual Conference of the American Society for Photogrammetry and Remote Sensing-Resource Technology Institute. Participants were given a valuable opportunity to interact with industries and private companies taking part in the exhibition for possible short- and long-term collaboration in areas of mutual interest. Through the exhibition, participants improved their understanding of the constant state of change in the mapping sciences, which promote applications of photogrammetry, remote sensing, GIS and supporting technologies.

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**Committee on the Peaceful Uses of Outer Space**

# Draft technical report on space debris of the Scientific and Technical Subcommittee

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## Introduction

1. The item on space debris was included on the agenda of the Scientific and Technical Subcommittee at its thirty-first session, in February 1994, in accordance with General Assembly resolution 48/39 of 10 December 1993. The Subcommittee, at its thirty-first session, expressed its satisfaction at having the subject of space debris as a separate agenda item after many years of discussion in various international forums, including the Subcommittee and the Committee on the Peaceful Uses of Outer Space. The Subcommittee agreed that consideration of space debris was important and that international cooperation was needed to evolve appropriate and affordable strategies to minimize the potential impact of space debris on future space missions (A/AC.105/571, para. 64). At its subsequent sessions, the Subcommittee continued its consideration of that agenda item on a priority basis.

2. The Subcommittee agreed that it was important to have a firm scientific and technical basis for future action on the complex attributes of space debris and that it should, *inter alia*, focus on understanding aspects of research related to space debris, including: debris measurement techniques; mathematical modelling of the debris environment, characterizing the space debris environment; and measures to mitigate the risks of space debris, including spacecraft design measures to protect against space debris (A/AC.105/605, para. 79). In order to advance in its consideration of space debris, the following work plan was adopted by the Subcommittee at its thirty-second session (A/AC.105/605, para. 83):

> 1996: Measurements of space debris, understanding of data and effects of this environment on space systems. Measurements of space debris comprise all processes by which information on the near-Earth particulate environment is gained through ground- and space-based sensors. The effect (impact of particles and resulting damage) of this environment on space systems should be described;
>
> 1997: Modelling of space debris environment and risk assessment. A space debris model is a mathematical description of the current and future distribution in space of debris as a function of its size and other physical parameters. Aspects to be addressed are: an analysis of fragmentation models; short- and long-term evolution of the space debris population; and comparison of models. The various methods for collision risk assessment should be critically reviewed;
>
> 1998: Space debris mitigation measures. Mitigation comprises reduction of the space debris population growth and protection against particulate impact. Measures for the reduction of space debris growth include methods for debris prevention and removal. Protection against space debris includes physical protection with shielding and protection through collision avoidance.

3. Each session was to review the current operational debris mitigation practices and consider future mitigation methods with regard to cost-efficiency. The Subcommittee agreed that the work plan should be implemented with flexibility and that notwithstanding the selection of a specific topic for the next session, delegations wishing to address the Subcommittee at that time on other aspects of scientific research related to space debris should be free to do so (A/AC.105/605, paras. 83-84).

4. The Subcommittee noted that a certain amount of research on space debris had already been undertaken in some countries, which had allowed for a better understanding of the sources of debris, the areas in near-Earth orbit that were reaching high levels of space debris density, the probabilities and effects of collisions and the necessity to minimize the creation of space debris (A/AC.105/605, para. 88). The Subcommittee agreed that Member States should pay more attention to the problem of collision of space objects, including those with nuclear power sources on board, with space debris and to other aspects of space debris. It also agreed that national research on space debris should continue and that Member States should make available to all interested parties the results of that research (A/AC.105/605, para. 85).[1]

5. The Subcommittee encouraged Member States and relevant international organizations to provide information on practices that they had adopted and that had proven effective in minimizing the creation of space debris (A/AC.105/605, para. 88). The information was compiled by the Secretariat and made available as United Nations documents. A list of the documents relevant to the subject "Space debris" is provided in the annex.

6. In order to have a common understanding of the term "space debris", the Subcommittee at its thirty-second session proposed a definition of the term that it modified at its subsequent sessions to read as follows: "Space debris are all man-made objects, including their fragments and parts, whether their owners can be identified or not, in

Earth orbit or re-entering the dense layers of the atmosphere that are non-functional with no reasonable expectation of their being able to assume or resume their intended functions or any other functions for which they are or can be authorized" (A/AC.105/672, para. 112). However, there is still no consensus agreement on the definition.

7. At its thirty-third session, the Subcommittee initiated the development of its technical report on space debris in order to establish a common understanding that could serve as the basis for further deliberations of the Committee on that important matter. The technical report was structured according to the specific topics addressed by the work plan during the period 1996-1998 and carried forward and updated each year. The text was drafted during the sessions of the Subcommittee by an unofficial group of experts provided by Member States. In drafting the technical report, working papers prepared for the sessions and scientific and technical presentations made by leading space debris experts were evaluated.

8. Especially valuable contributions to all parts of the technical report, in particular graphical and numerical data, were made by the Inter-Agency Space Debris Coordination Committee (IADC), which had been formally founded in 1993 to enable space agencies to exchange information on space debris research activities, to review the progress of ongoing cooperative activities, to facilitate opportunities for cooperation in space debris research and to identify debris mitigation options. The founding members of IADC were the European Space Agency (ESA), Japan, the National Aeronautics and Space Administration (NASA) of the United States of America and the Russian Space Agency (RSA). China joined in 1995; it was followed by the British National Space Centre, the Centre nationale d'études spatiales (CNES) of France and the Indian Space Research Organization (ISRO) in 1996 and by the German Aerospace Research Establishment (DLR) in 1997. Recently, the Italian Space Agency (ASI) applied for membership.

9. At its thirty-first session, the Subcommittee agreed that the final technical report of the Subcommittee on space debris should be adopted at its thirty-sixth session, in 1999, after final editing during the inter-sessional period and consideration by relevant organizations (such as IADC and the International Academy of Astronautics (IAA)).

# 1. Measurements of space debris

## 1.1 Ground-based measurements

10. Remote sensing of space debris from ground-based measurements generally falls into two categories: radar measurements and optical measurements. Typically, radar measurements have been used for space debris in low Earth orbit (LEO), while optical measurements have been used for high Earth orbit (HEO). For passive optical measurements, the signal intensity return is inversely proportional to the square of the distance or altitude of the object since the incident illumination from the Sun is essentially independent of altitude. For radar measurements, the signal intensity return is inversely proportional to the fourth power of distance since radars must provide their own illumination. The result is that an optical telescope of modest size can outperform most radars for detection of debris at high altitudes. Some optical measurements of small debris in LEO have been done, but in general radars outperform telescopes for measurements in LEO.

### 1.1.1 Radar measurements

11. Ground-based radars are well suited to observe space objects because of their all-weather and day-and-night performance. The radar power budget and operating wavelength are limiting factors for detection of small objects at long ranges.

12. Basically two types of radars are used for space object measurements:

(a) Radars with mechanically controlled beam direction using parabolic reflector antennas. Only objects in the actual field of view—given by the mechanical direction of the parabolic reflector antenna—can be detected and measured;

(b) Radars with electronically controlled beam direction using phased array antennas. Multiple objects at different directions can be detected and measured simultaneously.

13. The first type of radar is used mainly for tracking and/or imaging satellites, and the second type is used mainly for both tracking and search tasks.

14. The following radar modes are used for observation of space debris: tracking mode; beam-park mode; and mixed mode (sometimes called stare-and-chase).

15. In the tracking mode the radar follows an object for a few minutes, gaining data on angular direction, range, range rate, amplitude and phase of the radar echoes. From the evaluation of direction and velocity (angular rate and range rate) as a function of time, orbital elements can be derived.

16. In the beam-park mode, the antenna is kept fixed in a given direction and echoes are received from objects passing within its field of view. This gives statistical information on the number and size of the detected objects but less precise data on their orbit.

17. In the mixed mode, the radar would start in the beam-park mode and change to the tracking mode when an object passes the beam, thereby gaining more precise orbital data. Once the data are collected, the radar might return to the beam-park mode.

18. Radars have been used in both a monostatic (a single antenna for both transmitter and receiver) and bistatic (transmitting from one antenna and receiving from a second antenna) configuration. In the bistatic mode, an additional receiver antenna, separate from the emitting antenna, is used. This allows a greater sensitivity, which enables the detection of smaller objects and flexibility for networking different kinds of antennas.

19. From radar measurements principally, the following space object characteristics can be derived (all of the following parameters will have some degree of uncertainty):

(a) Orbital elements, describing the motion of the object's centre of mass around Earth;

(b) Attitude, describing the motion of the object around its centre of mass;

(c) Size and shape of the object;

(d) Orbital lifetime;

(e) Ballistic coefficient, as defined in paragraph 47 (g) below, specifying the rate at which the orbital semi-major axis decays;

(f) Object mass;

(g) Material properties.

20. The deterministic data can go into a catalogue of space objects, as well as the statistical information on numbers of detected objects of a given size in a given region at a certain time.

21. Both the Russian Federation and the United States (United States Space Command) operate networks of radars (and optical telescopes) for detecting, tracking and cataloguing orbiting space objects. These catalogues date from the first artificial satellite launch in 1957 and include space debris as small as 10-30 cm in diameter.

22. Radar measurements of orbital debris population statistics at sizes smaller than 30 cm (the nominal limit for the Russian and United States catalogues) have been conducted by the United States using Haystack, Haystack Auxiliary (HAX) and Goldstone radars, by the Russian Federation using some Russian radars and by Germany using the Research Establishment for Applied Science of Wachtberg-Werthhoven (FGAN) radar and the Effelsberg Radio Telescope. Haystack, HAX and Goldstone radars have provided a statistical picture of LEO debris environment at sizes down to 0.5 cm (with some data down to 0.2 cm). FGAN radar measurements have not extended to quite such small sizes but in general agree with the NASA results. The picture that emerges from these and other measurements is that the debris population exceeds the natural meteoroid population for all sizes (except between 30 and 500 μm).

23. The MU radar of Kyoto University of Japan has observed the radar cross-section variation of unknown objects for a period of 20 seconds. A bistatic radar system of the Institute of Space and Astronautical Sciences (ISAS) of Japan has the capability to detect objects as small as 2 cm at an altitude of 500 km.

24. The existing and planned radar capabilities for observation of debris for sizes smaller than 10-30 cm in diameter are given in table 1.

### 1.1.2 Optical measurements

25. Debris can be detected by a telescope when the debris object is sunlit while the sky background is dark. For objects in LEO, this period is limited to an hour or two just after sunset or before sunrise. However, for objects in HEO, such as those in geosynchronous orbit, observations can often be continued during the entire night. The requirement of clear, dark skies is another limitation on optical measurements.

Table 1
**Radar facilities for debris observation**

| *Country* | *Organization* | *Facility* | *Type* | *Primary operation mode* | *Configuration* | *Field of view* | *Wave-length (m)* | *Sensitivity (diameter) (m)* | *Status* |
|---|---|---|---|---|---|---|---|---|---|
| Germany | FGAN | TIRA | Dish | Mixed | Monostatic | 0.5 | 0.23 | 0.02 at 1,000 km | Operational |
| Germany | MPIfR | Effelsberg | Dish | Stare | Bistatic with TIRA | 0.16 | 0.23 | 0.009 at 1,000 km | Experimental |
| Japan | Kyoto University | MU radar | Phased array | Stare | Monostatic | 3.7 | 6.4 | 0.02 at 500 km | Operational |
| Japan | ISAS | Uchinoura | Dish | Mixed | Bistatic | 0.4 | 0.13 | 0.02 at 500 km | Experimental |
| Japan | ISAS | Usuda | Dish | Mixed | Bistatic | 0.13 | 0.13 | 0.02 at 500 km | Experimental |
| Ukraine/ Russian Federation | .. | Evpatoria | Dish | Stare | Bistatic | 0.1 | 0.056 | 0.003 at 1,000 km | Developmental |
| United States | NASA/ NSF | Arecibo | Dish | Stare | Bistatic | 0 | 0.13 | 0.004 at 575 km | One-time experiment |
| United States | NASA/ DoD | Haystack | Dish | Stare | Monostatic | 0.1 | 0.03 | 0.006 at 1,000 km | Operational |
| United States | NASA/ DoD | HAX | Dish | Stare | Monostatic | 0.1 | 0.02 | 0.05 at 1,000 km | Operational |
| United States | NASA | Goldstone | Dish | Stare | Bistatic | 0 | 0.035 | 0.002 at 500 km | Operational |
| United States | DoD | TRADEX | Dish | Mixed | Monostatic | 0.61/ 0.30 | 0.23/ 0.10 | 0.03 at 500 km | Operational |

26. The United States Space Command employs aperture telescopes of 1 m fitted with intensified vidicon detectors to track HEO objects. These measurements are used to maintain the HEO part of the Space Command catalogue. The capability of these telescopes is limited to detection of objects of 1 m at geosynchronous altitudes, corresponding to a limiting stellar magnitude of 16. Charge-coupled device (CCD) detectors are planned for these telescopes, which will improve their performance. RSA has a similar telescope capability used to maintain the orbits of HEO objects in its catalogue.

27. In general, the United States Space Command and the Russian geostationary orbit (GEO) catalogues are concerned with intact spacecraft and rocket bodies. However, there are reasons to believe that small orbital debris resulting from explosions also exist in the GEO region. A Russian Ekran satellite in GEO was observed to explode in 1978. Many uncatalogued objects have been seen in high elliptical orbits at an inclination of 7 degrees, possibly the result of Ariane geotransfer stage break-ups. The United States Space Command telescope on Maui, in Hawaii, accidentally observed the break-up of a Titan transtage (1968-081E) in February 1992. There are other stages near GEO that may still have the potential to explode. Some of these stages appear to be lost and may have exploded.

28. An exceptional combination of sensitivity and field of view is required to survey the GEO region for the small orbital debris that are suspected to exist there. A limiting stellar magnitude of 17 or greater is needed to detect

debris smaller than 1 m near geosynchronous altitude, and as wide a field of view as possible is needed to allow the rapid surveying of large areas. Most astronomical telescopes that have sufficient sensitivity have a small field of view. This is useful for accurate determination of satellite positions (once their approximate locations are known), but not for surveying large areas of the sky.

29. Some preliminary measurements have been done to survey the region near GEO for debris objects smaller than 1 m. NASA used a small telescope capable of detecting objects as faint as 17.1 stellar magnitude (equivalent to an object about 0.6 m in diameter at geosynchronous altitude), with a field of view of about 1.5 degrees. The results showed that there does exist an appreciable population of debris near those altitudes. Further debris surveys are justified. IADC is currently conducting an exploratory GEO orbital debris campaign.

30. The existing and planned optical capabilities for optical observation of debris are summarized in table 2.

Table 2
**Optical facilities for debris observation**

| *Country* | *Organization* | *Telescope aperture (m)* | *Field of view (degrees)* | *Detection type* | *Limiting magnitude* | *Status* |
|---|---|---|---|---|---|---|
| | ESA | 1 | 1 | CCD | 19 | In development |
| France | French National Centre for Scientific Research | 0.9 | 0.5 | CCD | 19 | In development |
| Japan | SUNDAI | 0.75 | 0.04 | CCD | 17 | Operational |
| Japan | CRL | 1.5 | 0.28 | CCD | 18.7 | Operational |
| Russian Federation | RAS[a] | 1 | 0.2 | CCD | 19 | Operational |
| | RAS[a] | 0.6 | 0.2 | CCD | 18 | Operational |
| Russian Federation | RSA[b] | 0.6 | 0.2 | TV | 19 | Operational |
| Switzerland | University of Berne | 1 | 0.5 | CCD | 19.5 | Operational |
| United Kingdom of Great Britain and Northern Ireland | Royal Greenwich Observatory/MOD | 0.4 | 0.6 | CCD | 18 | Two telescopes operational. United Kingdom and overseas |
| United States | NASA | 0.3 | 1.5 | CCD | 17.1 | Operational |
| United States | NASA | 3 | 0.3 | CCD | 21.5 | Operational |

[a] Russian Academy of Sciences
[b] Russian Space Agency

## 1.2 Space-based measurements

### 1.2.1 Retrieved surfaces and impact detectors

31. Information on submillimetre-sized particles can be gained with the analysis, after return to Earth, of surfaces or spacecraft exposed to the space environment. Similar information can also be obtained through dedicated debris and dust detectors. Most of them contain, as a key element, a detection surface. Some of them are designed to catch an impact particle for further analysis. For cost reasons, surfaces are retrieved for later analysis only from LEO.

32. Examples of retrieved spacecraft and surfaces are given in table 3.

Table 3
**Examples of retrieved spacecraft and surfaces**

| *Name* | *Orbit* | *In orbit* | *Stabilization* | *Exposed area* |
|---|---|---|---|---|
| Salyut 4 and 6 | 350 km<br>51.6 degrees | 1974-1979 | Various | ~7 $m^2$ of sensors and cassettes |
| STS-7 Window (NASA) | 295-320 km<br>28.5 degrees | June 1983 | Various | ~2.5 $m^2$ |
| Solar Maximum Mission (NASA) | 500-570 km<br>28.5 degrees | Feb. 1980-<br>Apr. 1984 | Sun-pointing | 2.3 $m^2$ |
| STS-52 (Canada/NASA) | 350 km<br>28.4 degrees | Oct. 1992 | Various | 1 $m^2$ |
| LDEF (NASA) | 340-470 km<br>28.5 degrees | Apr. 1984-<br>Jan. 1990 | Gravity-gradient | 151 $m^2$ |
| EURECA (ESA) | 520 km<br>28.5 degrees | July 1992-<br>June 1993 | Sun-pointing | 35 $m^2$ of spacecraft plus 96 $m^2$ of solar arrays |
| HST Solar Array (NASA/ESA) | 610 km<br>28.5 degrees | May 1990<br>-Dec. 1993 | Sun-pointing | 62 $m^2$ |
| Mir/EUROMIR 95 (RSA/ESA) | 390 km<br>51.6 degrees | Oct. 1995-<br>Feb. 1996 | Gravity-gradient | 20 x 30 cm (cassette) |
| Mir | 390 km<br>51.6 degrees | 1986-1998 | Various | ~15 $m^2$ of cassettes and other elements |
| Mir (Canada/Ukraine) | 390 km<br>51.6 degrees | Nov. 1997-<br>Feb. 1999 | Various | 1 $m^2$ |
| SFU (Japan) | 480 km<br>28.5 degrees | Mar. 1995-<br>Jan. 1996 | Sun-pointing (except 1 month IR telescope operation) | 50 $m^2$ |
| Space Shuttle Orbiter (NASA) | 300-600 km<br>28.5-51.6 degrees | 1992-present | Various | 100 $m^2$ |

33. After exposure to the space environment, spacecraft surfaces are covered with a large number of impact craters caused by meteoroids and debris. The size of individual impact craters and holes ranges from micrometres to several millimetres. A basic problem is to distinguish between impacts of meteoroids and man-made debris. A proven method to determine their origin is chemical analysis. However, there are some difficulties associated with this method. Because of the high impact speed, little of the impacting material survives unaltered. The particle vaporizes and then recondenses on the surrounding surfaces. In many cases, therefore, the origin of an impacting particle cannot be uniquely determined. In order to relate the size of the impact feature with the size of the particle, ground-calibration tests (hypervelocity impact tests) have been performed for different materials.

34. From impact statistics and calibration experiments, the flux for meteoroids and debris can be determined as a function of particle size. An important issue to be considered is that of secondary impacts. If these are not properly treated, the derived flux figures will be overestimated.

35. The Long-Duration Exposure Facility (LDEF) was covered by more than 30,000 craters visible to the naked eye, of which 5,000 had a diameter larger than 0.5 mm. The largest crater, 5 mm in diameter, was probably caused by a particle of 1 mm. LDEF showed that some impacts were clustered in time, and it also pointed to the existence of a submillimetre population in elliptical orbits.

36. On the European Retrievable Carrier (EURECA), the largest impact crater diameter was 6.4 mm. Among the retrieved surfaces, the returned solar array of the Hubble Space Telescope (HST) had been the one with the highest orbit altitude. An interesting finding was that the impact flux for HST was considerably higher (factor of 2-8) than for EURECA for crater pit sizes larger than 200-300 µm.

37. The Space Flyer Unit (SFU) launched by an H-II rocket in March 1995 was retrieved by the Space Shuttle in January 1996. A post-flight analysis (PFA) is under way.

38. The cases discussed above give evidence of the effect of the particulate environment on spacecraft in orbit. In all cases, no functional degradation of the spacecraft was observed. Available information on the submillimetre population is limited to altitudes below 600 km. In particular, no information is available in the regions of highest density of space debris in LEO (at an altitude of about 800-1,000 km) as well as in geostationary orbit. In 1996, an ESA debris and dust detector was placed in geostationary orbit on the Russian spacecraft Express-2. CNES will place active and passive detectors on Mir in 1999. CNES plans to use the same detectors on the French satellite STENTOR in geostationary orbit (1999) and in heliosynchronous orbit on an Israeli satellite (1999).

39. Since 1971, regular measurements of submillimetre-sized meteoroid and debris particles have been carried out on the Russian space stations Salyut 1, 2, 3, 4, 6 and 7 and Mir. The measurements have been carried out by capacitive sensors with an overall exposed area of about 3 $m^2$, as well as by changeable returned cassettes with an exposed area of about 0.1 $m^2$ each. In January 1998, during the Space Shuttle mission, eight sections of solar panels from the space station Mir, with an overall area of about 10 $m^2$ and an exposure time of about 10 years, were returned to Earth for further investigation.

### 1.2.2 Space-based debris measurements

40. Space-based measurements in general have the advantage of higher resolution because of the smaller distance between the observer and the object. Also, there is no disturbing effect of the atmosphere (extinction and absorption of electromagnetic signals). The costs of space-based systems are in general higher than the costs of ground-based systems, and careful cost-performance trade-offs are needed.

41. The infra-red astronomical satellite (IRAS), launched in 1983 to perform a sky survey at wavelengths ranging from 8 to 120 µm, was operational during the 10 months in a Sun-synchronous orbit near an altitude of 900 km. The satellite was pointing radially away from Earth and scanning the celestial sphere. The complete set of unprocessed IRAS data has been analysed by the Space Research Organization of the Netherlands (SRON), in Groningen, in order to characterize the infra-red emission of debris objects and to extract a comprehensive set of debris sightings. The method of identifying space debris signatures is based on the recognition of their track over the IRAS focal plane. The 200,000 potential debris sightings are stored in a database. About 10,000 sightings are attributed to real objects. From the debris sightings, it is not possible to compute the orbital elements of a debris object in a unique manner.

42. In 1996, the United States launched the MSX spacecraft into a 900 km orbit. Its visible and infra-red sensors are being used to observe nearby small debris.

43. In September 1996, the impact ionization detector Geostationary Orbit Impact Detector (GORID) was placed into GEO on board the Russian telecommunication satellite Express 12. It is stationed at 80 degrees east longitude and measures the submillimetre-sized meteoroid and space debris population.

44. To measure the small-sized solid particle population in different orbits and on a more regular basis, a low resource standard *in situ* detector called DEBIE is under development. The first flight of DEBIE is planned on the small ESA technology satellite PROBA in polar orbit.

## 1.3 Summary of measurements

45. Figure I presents a compilation of the results of many of the measurement systems described in previous sections. It shows the cross-sectional flux (number of objects per year per square metre) for objects of a given size and larger. The figure summarizes measurements in LEO near 500 km altitude.

## 1.4 Cataloguing and databases

46. A catalogue is a record of the characteristics of the orbital population that have been derived from measurements or records. (For the purposes of the present report, the term catalogue includes the collection of orbital elements.) The purposes of a catalogue are to provide current orbital elements, which can be used to predict orbital motion, and to provide correlation with observations of orbiting objects; to act as a historical record of orbital activity for the purposes of environment monitoring; to serve as an input to modelling the behaviour of orbiting objects; and to provide a basis for predicting future launch and operational activity.

47. The following characteristics of orbiting objects may be recorded:

(a) Regularly updated state vectors: the characteristics of the orbit of an object derived at a particular instant in time and used for orbit propagation;

(b) Mass: the launch mass, beginning of life mass and dry mass (end of life);

(c) Radar cross-section: the returned signature of an orbiting object, from which shape, orientation and size can be derived; (the radar cross-section is dependent on the wavelength of the radar; therefore, the wavelength of the measurement must also be recorded);

(d) Albedo: a measure of the reflectivity of an object that characterizes the optical visibility of an object;

(e) Dimensions;

(f) Orientations;

(g) Ballistic coefficient: a measure of the aerodynamic and area-to-mass characteristics of the object that will influence the orbital lifetime of an object until its entry into the upper atmosphere;

(h) Material composition: although not currently of importance, to effectively represent shedding of micro-debris would require the definition of surface characteristics;

(i) Launch characteristics: this will include the launch vehicle, launch date and launch site.

48. There are two catalogues of space objects that are frequently updated by observations: the United States Space Command catalogue and the space object catalogue of the Russian Federation. Data are also archived in the Database and Information System Characterizing Objects in Space (DISCOS) of ESA based on those two catalogues. Figure II shows the growth of the number of objects in the United States catalogue with time (limited to sizes larger than 10-30 cm).

49. The National Space Development Agency (NASDA) of Japan is studying a debris database that can provide data to the international common debris database currently being discussed in IADC. NASDA is also studying a trajectory prediction analysis for re-entering objects and collision avoidance analysis for new launches.

50. NASDA currently depends on the United States Space Command orbital element data as the source of its debris database. NASDA will add the orbital data of its own spacecraft acquired through observations conducted by the National Astronomy Observatory.

51. A catalogue record can be stored on a number of media. A hard-copy (paper) format is not well suited to the dynamic nature of the orbital population. An electronic format is well suited to the recording of such information, modification and updating of characteristics, manipulation of data for the purposes of comparison and input to models, and access via networks by users for the purposes of interrogation and contribution.

Figure I

**Approximate measured debris flux in low Earth orbit, by object size**

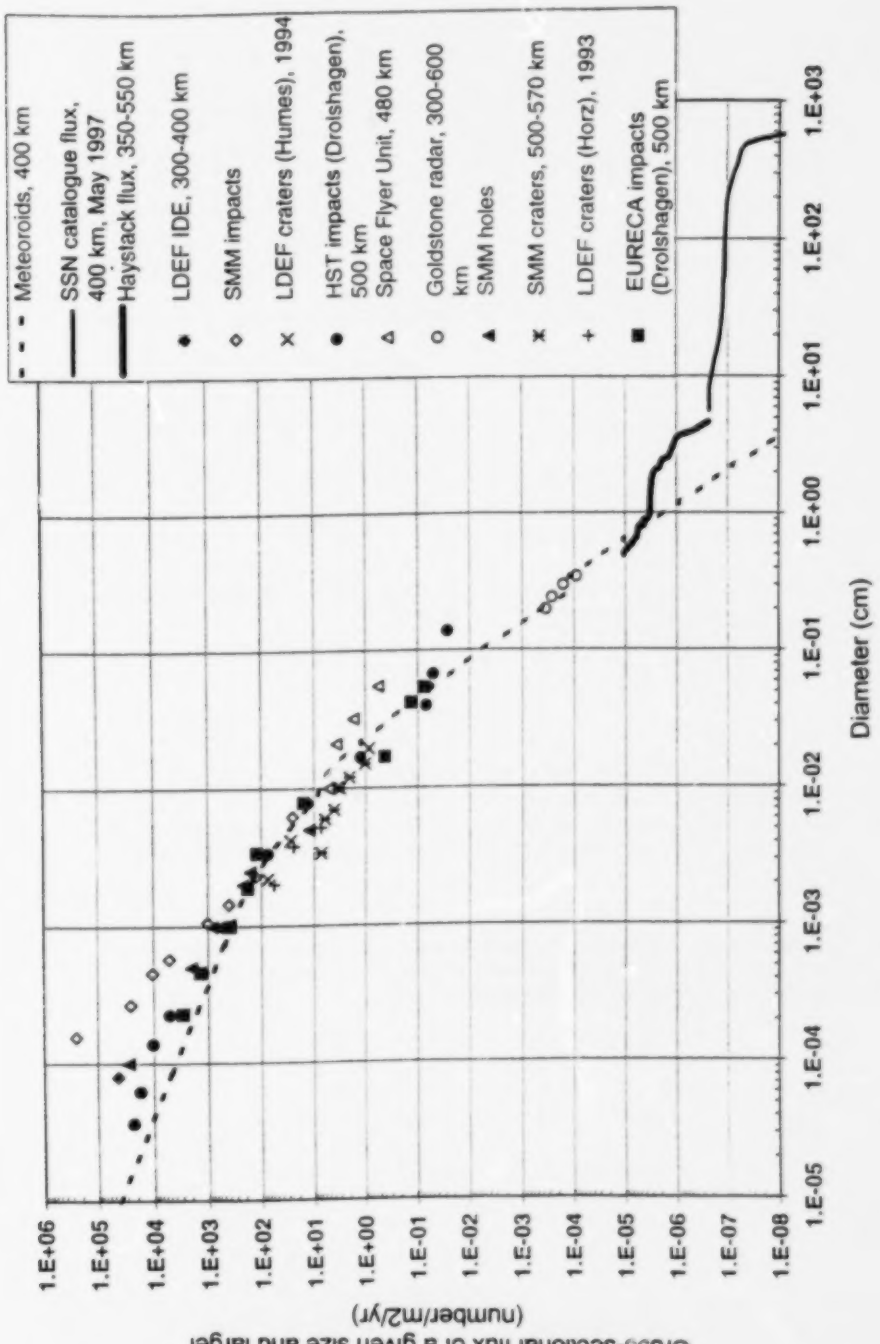
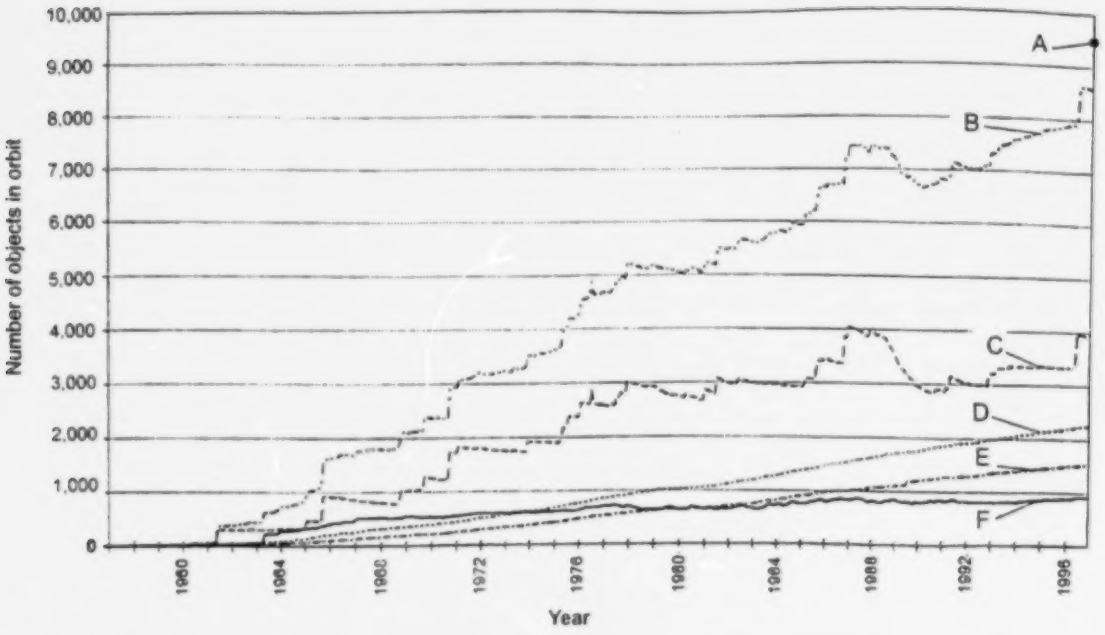


Figure II
**Number of objects in the United States catalogue, by type, 1959-1996**




A: Total number of objects, including objects not contained in the official catalogue

B: Total number of objects, based on the official catalogue

C: Fragmentation debris; fragments are counted since the year of event; fragmentation parents are counted as intacts until the date of event; since the event date the parents are counted as fragments

D: Spacecraft

E: Rocket bodies

F: Operational debris; operational debris related to a launch are counted since the year of launch; Salyut 4, 5, 6, 7 and Mir operational debris are not counted since the date of launch of the parent but since a more realistic date

52. Current catalogues contain information on satellites and debris as small as 10-30 cm in diameter. Some recent activities in the United States are aimed at improving the sensitivity of the United States catalogue to provide detection of 5 cm objects at altitudes below 600 km. Some studies have looked at improvements to provide detection of objects as small as 1 cm. However, improvements of catalogues beyond 5 cm are not likely in the near future. Therefore, modellers must continue to use statistical measurements for smaller sizes (see figures III and IV).

## 1.5 Effects of the space debris environment on the operation of space systems

53. Four factors determine how the space debris environment affects space systems operations. These are time in orbit, projected area, orbital altitude and orbital inclination. Of these, time in orbit, projected area and orbital altitude are the dominant factors.

Figure III

**Coverage of ranges of debris diameter and period of exposure: space-based data, 1980-1998**

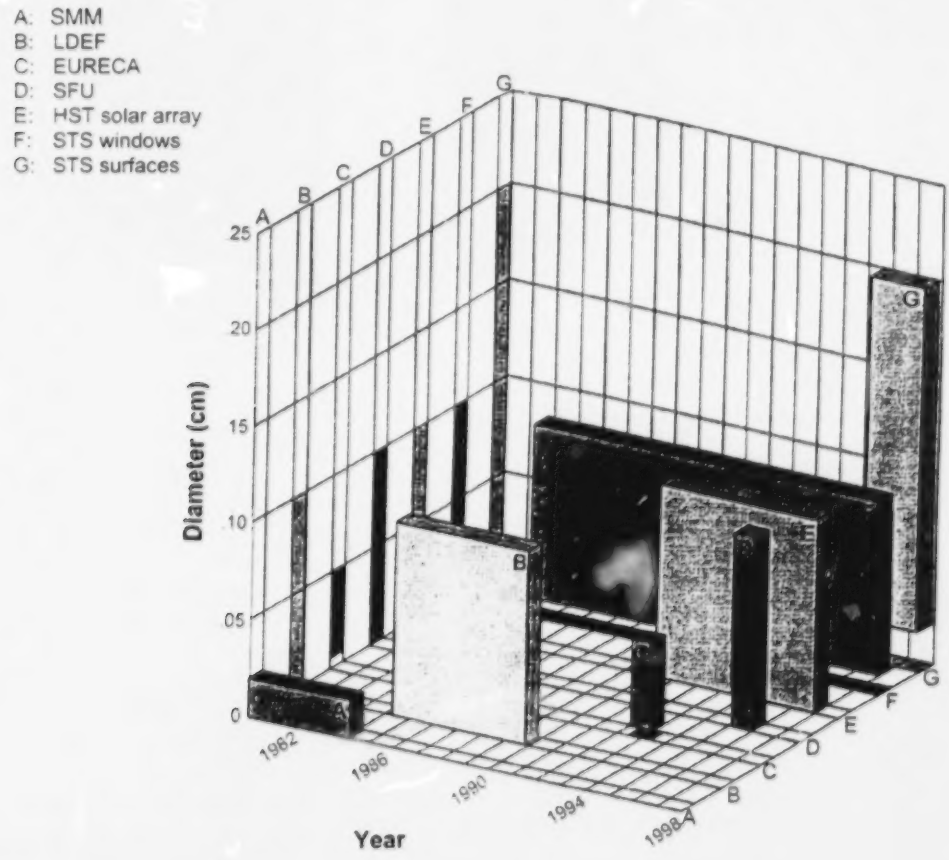
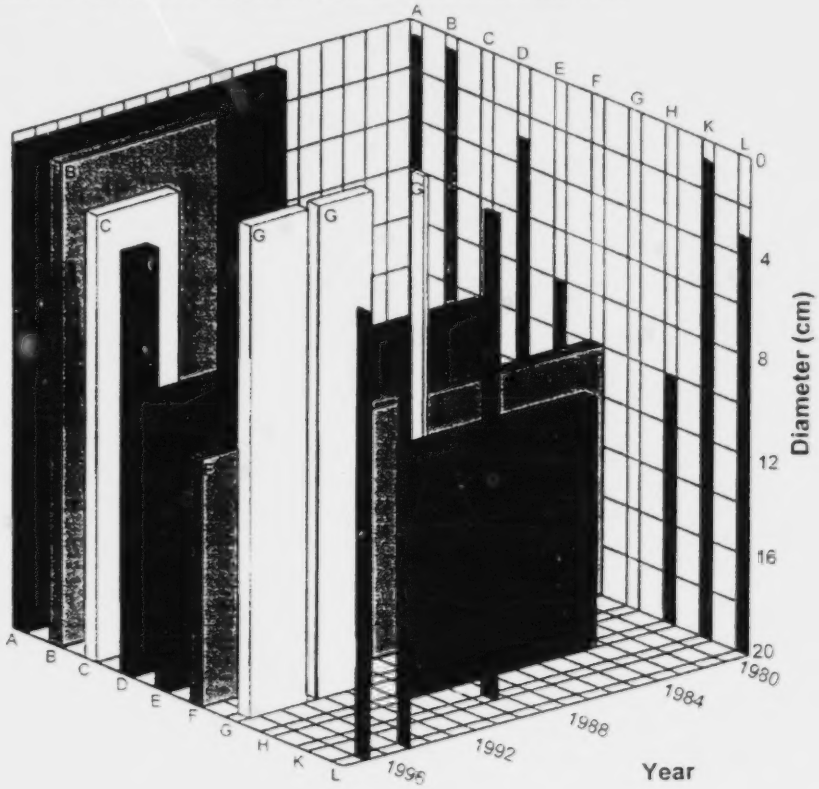


Figure IV
**Coverage of ranges of debris diameter and period of exposure: ground-based data, 1980-1998**

A Mir photo studies
B Haystack
C Haystack Auxiliary (HAX)
D Liquid Mirror Telescope (LMT)
E CCD Debris Telescope (CDT)
F Space Surveillance Network (SSN) (United States)
G Goldstone
H Ground Electro-Optical Deep Space Surveillance System (GEODSS)
K Arecibo
L Research Establishment for Applied Science (FGAN) Germany




### 1.5.1 Effects of large debris objects on the operation of space systems

54. Large debris objects are typically defined as objects larger than 10 cm in size. Such objects are capable of being tracked, and orbital elements are maintained. During the course of shuttle missions, orbiters have executed collision avoidance manoeuvres in order to avoid catastrophic collisions with these large debris objects. Two unmanned satellites have also performed collision-avoidance manoeuvres to avoid large debris. The European remote sensing satellite (ERS-1) in June 1997 and Satellite pour l'observation de la Terre (SPOT-2) in July 1997. In 1996, the first recorded natural collision occurred between two catalogued objects, the operational Cerise satellite and a fragment from an exploded Ariane upper stage.

### 1.5.2 Effects of small debris objects on the operation of space systems

55. To date, small debris objects (smaller than a few millimetres in diameter) have caused damage to operational space systems. These impacts have had no known effect on mission success. This damage can be divided into two categories. The first category is damage to surfaces or subsystems. The second category is the effect on operations.

#### 1.5.2.1 Damage to surface or subsystems

56. Examples of damage that affect the surface of operational systems are:

(a) Damage to shuttle windows;

(b) Damage to HST high gain antenna;

(c) Severing of the Small Expendable Deployer System-2 (SEDS-2) tether;

(d) Damage to other exposed shuttle surfaces.

In the damage described in subparagraphs (a), (b) and (d) above, there is clear evidence of damage due to orbital debris. In subparagraph (c), it is unclear whether the damage is caused by man-made debris or a micrometeoroid.

#### 1.5.2.2 Effects of space debris on human space operations

57. In order to protect crews from debris during flight, operational procedures have been adopted. In the case of the Space Shuttle, the orbiter is often oriented during flight, with the tail pointed in the direction of the velocity vector. This flight orientation was adopted to protect the crew and sensitive orbiter systems from damage caused by collisions with small debris.

58. Operational restrictions have also been adopted for extravehicular activities (EVAs). Whenever possible, EVAs are conducted in such a way as to ensure that the EVA crew is shielded from debris by the orbiter.

### 1.6 Other effects of space debris

59. Astronomers are observing during wide field imaging an increasing number of trails per plate caused by orbital debris. These trails degrade the quality of the observation. Orbital debris trailing will entirely negate a photometric observation when debris cross the narrow photometric field.

## 2. Modelling of the space debris environment and risk assessment

### 2.1 Modelling of the space debris environment

#### 2.1.1 Introduction and methodology

60. Space debris models provide a mathematical description of the distribution of objects in space, the movement and flux of objects and the physical characteristics of objects (e.g. size, mass, density, reflection properties and intrinsic motion). These models can be deterministic in nature (i.e. each object is described individually by its orbital parameters and physical characteristics), statistical in type (i.e. characterization of an ensemble by a sample number of objects) or a combination (i.e. hybrid). These models can be applied to risk and damage assessments, prediction of debris detection rates for ground-based sensors, prediction of avoidance manoeuvres of operational spacecraft and long-term analysis of the effectiveness of debris mitigation measures.

61. Space debris models must consider the contribution to the population of orbiting objects of the following source mechanisms:

(a) Launches (including launch vehicle upper stages, payloads and mission-related objects);

(b) Manoeuvres (to account for solid rocket motor firings);

(c) Break-ups (produced by explosions and collisions);

(d) Material separation from surfaces (ageing effects, e.g. paint flakes);

(e) Material due to leakage (e.g. nuclear power source (NPS) coolant).

62. The following sink mechanisms must also be considered:

(a) Orbital decay due to atmospheric drag or other perturbations;

(b) Retrievals from orbit;

(c) Deorbiting;

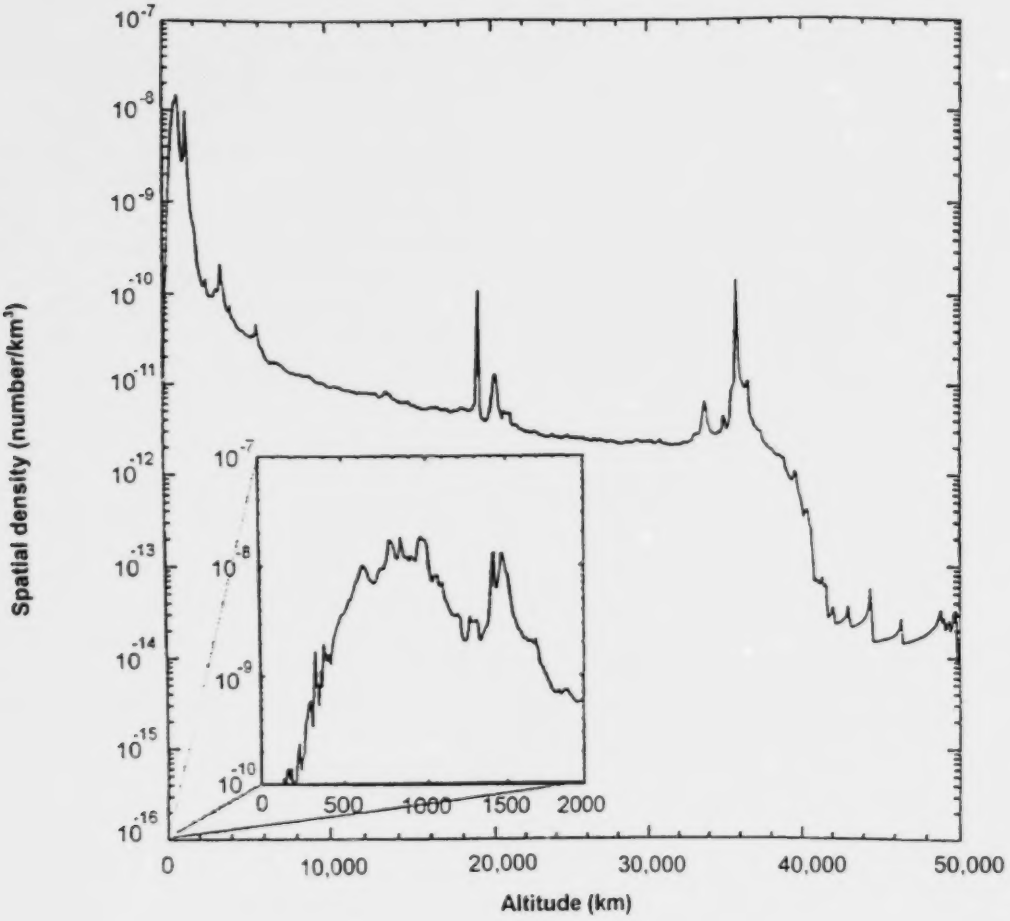
(d) Fragmentation (leading to a loss of large objects).

A debris environment model must contain all or some of these elements.

63. Space debris models make use of available data sources. These include:

(a) Deterministic data on decimetre-sized and larger objects within the United States Space Command Satellite catalogue and the Russian Space Surveillance catalogue (see figure V for the related spatial density distribution);

Figure V
**Spatial density of catalogued objects (as at 21 August 1997)**



(b) Statistical data on centimetre-sized objects derived from dedicated radar campaigns in LEO;

(c) Statistical data on encountered submillimetre debris populations inferred from analysis of retrieved surfaces and from *in situ* impact sensors;

(d) Statistical data on decimetre and larger objects in LEO using ground-based telescopes;

(e) Ground-based simulations of hypervelocity collisions with satellite and rocket bodies;

(f) Ground-based simulations of explosive fragmentations.

64. These models are limited by the sparse amount of data available to validate the derived relationships. The models must rely upon historical records of satellite characteristics, launch activity and in-orbit break-ups; in addition, there are only limited data on spacecraft material response to impact and exposure to the orbital environment. Furthermore, major assumptions must be made in applying these models to predict the future environment. In particular, future traffic scenarios and the application of mitigation measures will have a major influence on the outcome of model predictions. Space debris models must be continually updated and validated to reflect improvements in the detail and size of observational and experimental data sets.

65. Environment models may take two forms: as discrete models, which represent the debris population in a detailed format, or as an engineering approximation. Furthermore, these models can be short term in nature (considering time-frames of up to 10 years) or long term (considering time-frames of over 10 years). In the preparation of all these models, the initial debris population is represented at a particular starting epoch and propagated forward in time in a stepwise manner, taking account of source and sink mechanisms and relevant orbit perturbations. Neither the short-term nor the long-term models account for the periodic concentrations of debris that exist hours to months following a break-up; such "very short-term" models are occasionally used to assess the hazard to specific space systems but are not discussed below.

66. The pertinent characteristics of the models are compared in table 4.

Table 4
**Debris environment models**

| *Model name* | *Source* | *Evolutionary period* | *Engineering model available* | *Minimum size* | *Orbital regime* |
|---|---|---|---|---|---|
| CHAIN | NASA | Long term | No | 1 cm | LEO |
| CHAINEE | ESA | Long term | No | 1 cm | LEO |
| EVOLVE | NASA | Short and long term | No | 1 mm | LEO |
| IDES | DERA | Short and long term | No | 0.01 mm | LEO |
| LUCA | TUBS | Long term | No | 1 mm | LEO/ MEO |
| MASTER | ESA | Short term | Yes | 0.1 mm | LEO/ GEO |
| Nazarenko | RSA | Short and long term | No | 0.6 mm | LEO |
| ORDEM96 | NASA | Short term | Yes | 1 μm | LEO |
| SDM/STAT | ESA/ CNUCE | Short and long term | No | | LEO/ GEO |

### 2.1.2 Short-term models

67. The following short-term models are available in the scientific and engineering community:

(a) *EVOLVE* was developed by the NASA Johnson Space Center to provide both short-term and long-term forecasts of the LEO environment with excessive source terms and detailed traffic models, based on quasi-deterministic population propagation techniques that are suitable for both LEO and GEO modelling;

(b) *ORDEM96* is a semi-empirical engineering model developed by NASA Johnson Space Center. It is based upon extensive remote and *in situ* observations and is used to support United States Space Shuttle and International Space Station design and operations;

(c) *MASTER* is an ESA semi-deterministic environment model based on 3-D discretization of spatial densities and transient velocities. The model is applicable to altitudes from LEO to GEO, providing environment estimates in the short term. A less detailed version of MASTER is available as an engineering format. Both models were developed by the Technical University of Braunschweig under ESA contract;

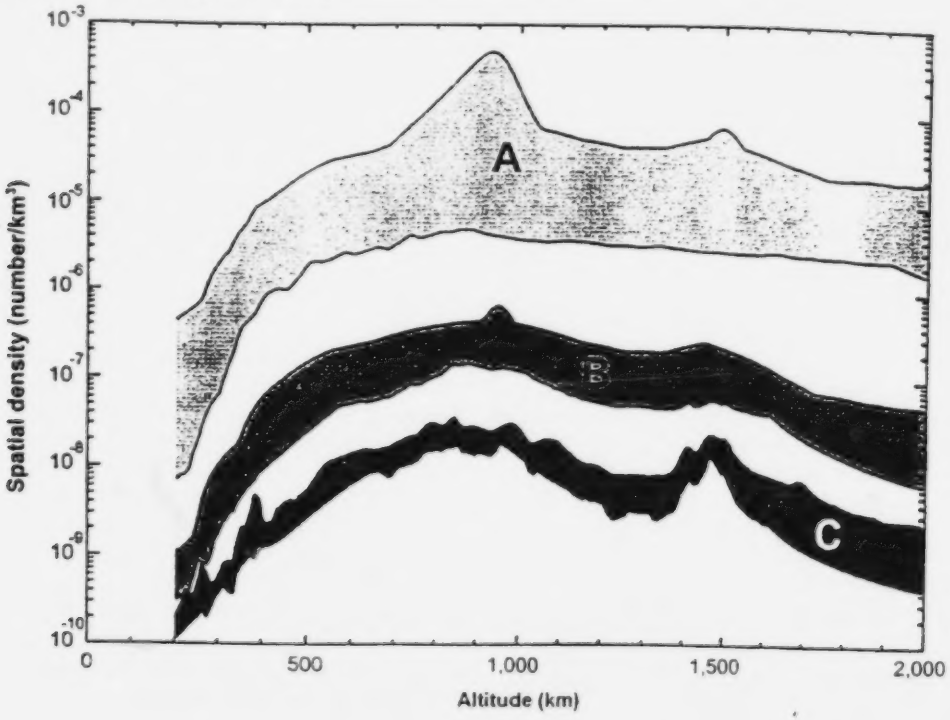
(d) *IDES* is a semi-deterministic model of the environment using detailed historical and future traffic models to provide short-term and long-term predictions of the orbital debris environment and the collision flux it presents to specific satellites. The model was developed by the Defence Evaluation and Research Agency (DERA), Farnborough, United Kingdom;

(e) *Nazarenko*, a model developed by the Centre for Programme Studies (CPS) of RSA, is a semi-analytic, stochastic model for both short-term and long-term prediction of the LEO debris environment, providing spatial density, velocity distributions and particle fluxes. The model takes account, in average form, of debris sources (except for the cascading effect) and of atmospheric drag; it has been adjusted on the basis of Russian and American catalogue data and published measurements of somewhat smaller fragments (more than 1 mm), while also taking account of a priori information;

(f) *SDM* is a semi-deterministic model to provide both short-term and long-term predictions of the orbital debris environment. The code, developed at CNUCE, makes use of a detailed traffic model, including satellite constellations, and considers several source model options for explosions, collisions and RORSAT leaks. SDM has been developed under ESA and ASI contracts.

68. These models can be used to "predict" the current environment. Several different models have been used to develop "envelopes of solution" for the current environment, as shown in figure VI.

Figure VI
**Model values for current spatial density**




*Sources:* NASA (ORDEM96); DERA (IDES); ESA (MASTER); CNUCE (SDM); and Nazarenko

A: ≥ 1mm
B: ≥ 1 cm
C: ≥ 10 cm

### 2.1.3 Long-term models

69. The scope of the long-term modelling of the orbital debris environment is the long-term (up to 100-year) prediction of the number of objects as a function of time, of altitude, of inclination and of object size. These projections are important for assessing the necessity and the effectiveness of debris mitigation techniques and the impact of new space activity.

70. In addition to the sources of space debris that are considered in the modelling of the current debris population, it is necessary to take into account collisions among larger objects (>10 cm). Currently, collisions among larger objects do not play a significant role in the increase of the number of objects, since their probabilities are low. However, in the future, the interactive risk for so-called destructive collisions, i.e. collisions that generate larger fragments, may increase. This so-called interactive collision risk among all objects of the population is proportional to the square of the number of objects. Hence, in the future, long-term mitigation should consist of the removal of mass and cross-section from orbit.

71. In order to assess the consequences of collisions among larger objects, it is necessary to have reliable break-up models for collisions of this type. However, it is very difficult to simulate on-orbit collisions without having test data for validation purposes available. Hence, a certain degree of uncertainty is introduced into the models by the collision simulation.

72. Other than the modelling of the present debris population, the long-term modelling requires assumptions describing the future space flight activities, including the debris generation mechanisms, in terms of, for example:

(a) Future number of launches and related orbits;

(b) Future number and size of payloads per launch;

(c) Future number of mission-related objects (fairing, bolts etc.);

(d) Future number of explosions of spacecraft and upper stages;

(e) New uses of space (e.g. commercial LEO communications satellite constellations).

73. All of these parameters are subject to variations with time due to technical/scientific, financial and political aspects. Hence, some uncertainties are added to those uncertainties that are due to the mathematical model itself (break-up models etc.).

74. A number of models have been developed for the purpose of long-term modelling of the debris environment. They can be characterized briefly as follows:

(a) *CHAIN* and *CHAINEE*: CHAIN was developed by the Technical University of Braunschweig under contract. Since 1993, this model has been maintained and improved by NASA. CHAINEE, the European extension of CHAIN, is used by ESA. The model, an analytical "particle-in-a-box" model, describes the population and the collision fragments up to an altitude of 2,000 km using four altitude bins in LEO and five mass classes. CHAIN and CHAINEE are extremely fast computer codes. It enables the identification of relative trends associated with specific mitigation policies. The resolution of CHAIN is limited due to the binning used;

(b) *EVOLVE*: The EVOLVE model has been developed by NASA. It is a semi-deterministic model (SDM), i.e. debris objects are described individually by a set of parameters. In addition to being capable of modelling the present debris environment, it can be used to investigate future evolutionary characteristics under various mitigation practices using Monte Carlo techniques. For this purpose mission model data are used;

(c) *IDES*: The IDES model was developed at the Space Department of DERA. Historical sources such as launches, break-ups and paint flakes are simulated and evolved to generate the current debris environment. This is used as the initial conditions, together with a detailed mission model, to simulate the future evolution of the debris environment. IDES can be used to study the collision interactions of multiple LEO satellite constellations and the effectiveness of debris mitigation measures;

(d) *LUCA*: For the detailed analysis of future scenarios, especially if a high resolution concerning the orbital altitude and the declination is required, the semi-deterministic computer code LUCA has been developed at the Technical University of Braunschweig. This code combines the advantages of a high spatial resolution and of a tolerable computer time need. In order to calculate the time-depart collision risk, a special tool has been implemented. This tool reflects the increased collision risks at higher declinations (e.g. close to the polar regions);

(e) *SDM/STAT*: The semi-deterministic model (SDM) and the stochastic approach (STAT) use the same initial population, as provided by a computer model, and

the same source and sink assumptions, including collisions. In SDM, orbits of a representative subset of the population are used to map the population forward in time; by means of parametric studies, effects of launch policies and mitigation measures can be analysed. STAT is a computer time-efficient "particle-in-a-box" alternative to SDM. It is based on a system of coupled differential equations for the populations of 80,000 bins in mass, semi-major axis and eccentricity. The two codes can be compared and given similar results;

(f) *Dual-size particle-in-a-box*: these are two models with the ability to handle LEO constellations;

(g) *Nazarenko*: the Nazarenko model, developed by CPS (Russian Federation), is a semi-analytic, stochastic model for both short-term and long-term predictions of the LEO environment, providing spatial density, velocity distributions and collision risk assessment. The model is based on Russian and United States catalogue data and on published data on small space debris (>1 mm). The model uses the same initial population, based on the satellite catalogues and an averaged space debris source. Source characteristics are based on the historical analysis of space debris contamination. Forecasting is performed by integrating the partial differential equations for the space debris distribution as a function of altitude. Atmospheric drag, distribution of ballistic coefficients and orbit eccentricity are taken into account in the orbit propagation.

75. The major findings of the above-mentioned long-term debris models can be summarized as follows:

(a) The debris population may grow in an accelerated manner in the future if space flight is performed as in the past. This is because of the increasing number of collisions that will occur among larger objects;

(b) Currently, depending on size, fragments from explosions are the main source of space debris. Beyond a certain point in time, collision fragments may dominate the population;

(c) Should the second stage of this evolution occur, the so-called collisional cascading effect may set in. This means that collisional fragments will contribute to the number of subsequent collisions. At that point in time, the population will grow exponentially;

(d) Suppressing explosions can reduce the number of objects in orbit, but cannot prevent collisional cascading, which is driven by the total mass in orbit and the number of large objects;

(e) Only by limiting the accumulation of mass in LEO can collisional cascading be prevented;

(f) At some point in the future, collisional fragments may dominate the environment. Without some technology development there will be no practical capability to halt growth of the environment; therefore, mitigation measures should be implemented before this point is reached.

76. The results of the long-term debris models do not agree quantitatively because of differences in assumptions and initial conditions. However, the basic trends and tendencies obtained by the models agree qualitatively. The number of major collisions predicted by several models (EVOLVE, CHAIN, CHAINEE and IDES) are presented as envelopes of predictions in figure VII. The number of fragments generated by future sources is less consistently predicted for small fragments.

77. The collision probabilities among the larger objects are initially low. Hence, it is essential to analyse a number of single Monte Carlo runs or to use mean value approaches in order to obtain reliable trends and tendencies. The above models take care of that effect.

## 2.2 Space debris risk assessments

### 2.2.1 Introduction

78. Risk assessments include the probability of an event, as well as its subsequent consequences. With the assistance of models of the orbital debris environment, the risk of collision among operational spacecraft and orbital debris can be evaluated. Spacecraft in LEO are routinely bombarded by very small particles (<100 μm) because of the large number of such debris, but the effects are normally slight due to the small masses and energies involved. Because of the smaller population of large debris objects, the likelihood of collision decreases rapidly as the size of the debris increases. However, the severity of collisions between large objects increases.

79. The principal risk factors are the spatial density and average relative collisional velocity along the orbit (altitude and inclination) of the space object of interest, the cross-sectional area of the space object and the duration of the flight. The consequences of a collision will depend upon the respective masses and compositions of the objects involved. Whereas the collision risk between an orbiting object and a meteoroid is essentially independent of altitude, the probability of collision between orbital

objects is strongly related to altitude, in general being an order of magnitude higher in LEO than in GEO.

### 2.2.2 Collision risk assessments in low Earth orbit

#### 2.2.2.1 Methodology

80. Risk assessments have been routinely performed on LEO spacecraft since the 1960s. The Poisson model is used in cases where there is a large number of independent events and each event has a small probability of occurring. Man-made debris and micrometeoroids meet these criteria for independence, except in cases of a recent break-up or a meteor storm.

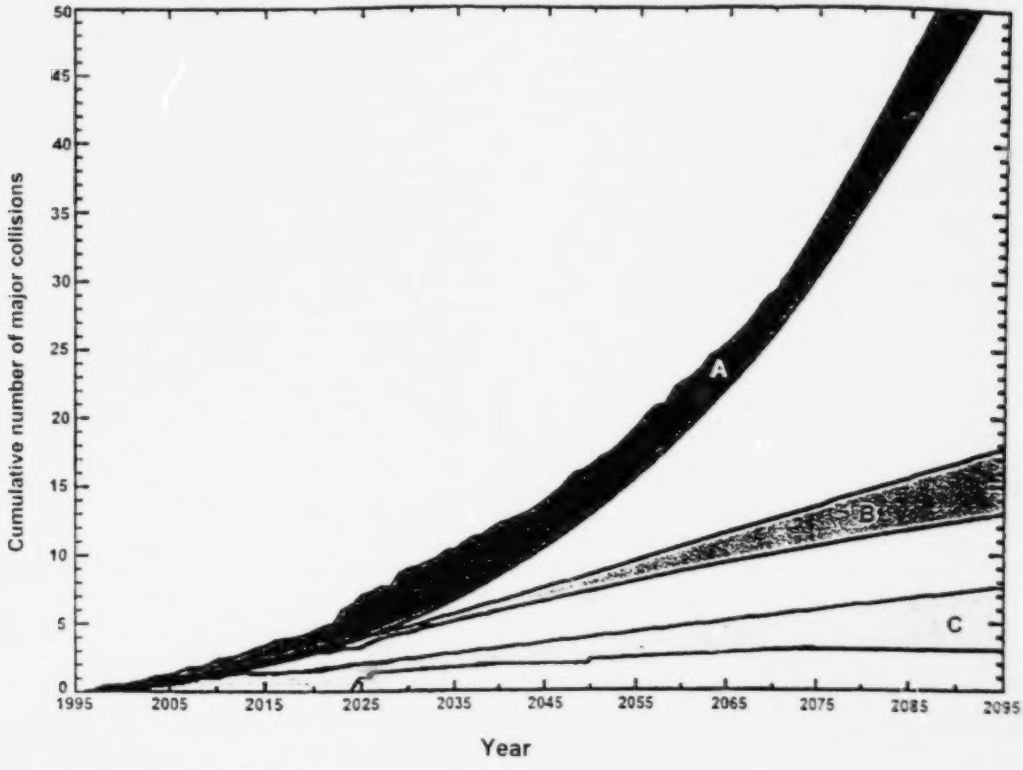
81. To compute the probability of an impact from space debris requires a meteoroid orbital debris (MOD) environment model, a spacecraft configuration and a mission profile. To compute the probability of a penetration and or a failure due to space debris requires detailed knowledge of the spacecraft configuration, including:

(a) The geometry of critical subsystems;

(b) The penetration resistance or ballistic limit equation of each subsystem;

(c) Data on the ability of each subsystem to tolerate damage.

Figure VII
**Typical ranges for number of major collisions for three scenarios, 1995-2095**




A: Business as usual
B: Business as usual for the next 20 years; then no more launches
C: No future launches

82. Based on this information, computer codes can calculate:

(a) The probability of space debris impacts for a particle of a given size;

(b) The probability of impact damage to any given subsystem;

(c) The split between damage from man-made debris and micrometeoroids.

#### 2.2.2.2 Results of risk assessments

83. Risk assessments in LEO are routinely utilized to enhance the safety of space operation. In cases involving human space flight, risk assessments have proved invaluable in ensuring the safety of shuttle operations. Shuttle missions are operationally reconfigured whenever a pre-flight risk assessment indicates that the risks of space debris are at an unacceptable level.

84. Risk assessments are being utilized to design the location and type of space debris shielding that will protect the crew as well as the crucial subsystems on the International Space Station.

85. Risk assessments are also utilized in the design of unmanned spacecraft. They aid in the placement and protective shielding design of critical subsystems and components, as well as in the system design of large communication satellite constellations. An example of risk assessment at LEO is given in table 5.

### 2.2.3 Collision risk assessments in geostationary orbit

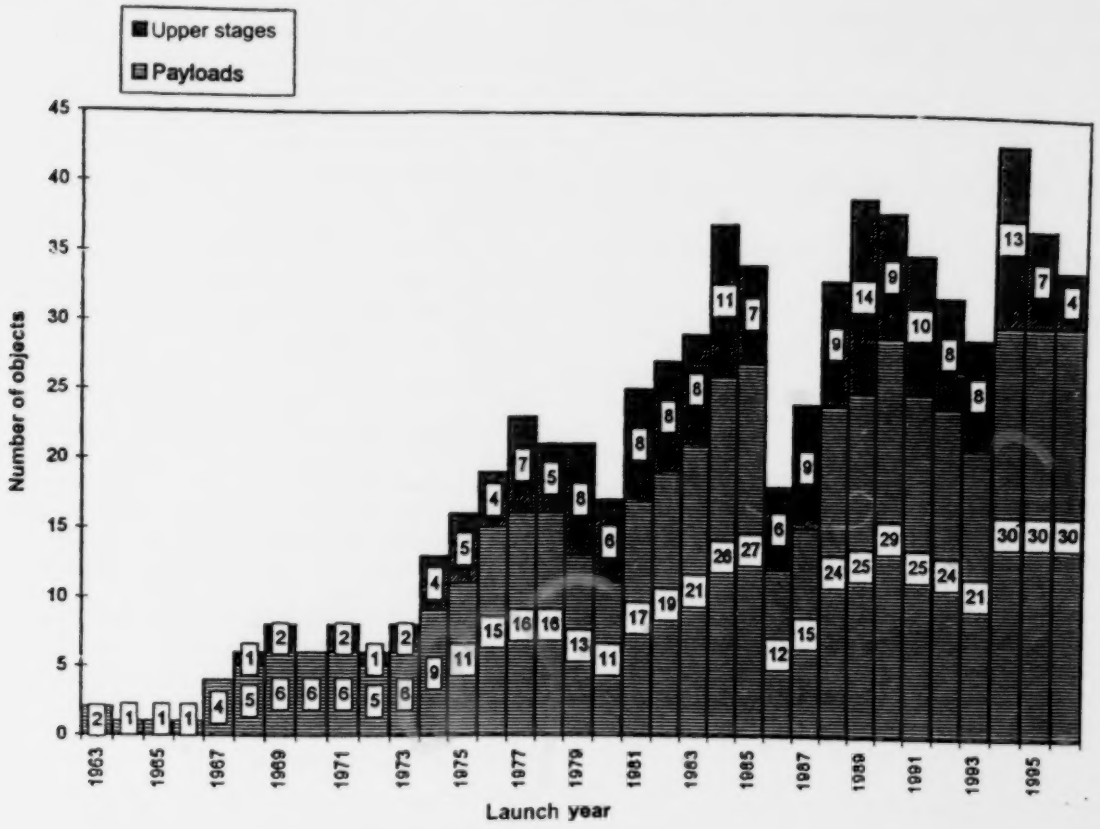
86. Currently, the population of space objects in and near the GEO regime (see figure VIII) is well known for only spacecraft and upper stages. The limited number of these objects, their wide spatial distribution and the lower average relative velocities (500 m/sec) combine to produce a substantially lower probability of collision in GEO. Moreover, as more spacecraft and upper stages are left in orbits above or below GEO, the number of uncontrolled intact objects intersecting the GEO regime is increasing at a very slow rate. Special collision possibilities exist in GEO because of the close proximity of operational spacecraft at selected longitudes, but these collision hazards can be eliminated by spacecraft control procedures. The limited number of large objects near GEO also permits the prediction of close approaches between operational spacecraft and tracked orbital debris in sufficient time to conduct an evasive manoeuvre.

87. The number of orbital debris of less than 1 m in diameter near GEO is not well known. Two break-ups (one a spacecraft and one an upper stage) have been identified, and some evidence suggests that additional break-ups may have occurred. Such debris would be perturbed into new orbits, possibly reducing the residence time in GEO but increasing the relative collision velocity, making the flux contribution nearly constant with inclination change. In many cases debris fragments would be widely dispersed in both altitude and inclination. Additional orbital debris measurements in GEO are needed before more accurate risk assessments can be performed. Also, new techniques to predict collision probability may need to be developed to take into account the non-random nature of close approaches in GEO.

Table 5
**Mean time between impacts on a satellite with a cross-section area of 10 square metres**

| | *Objects 0.1-1.0 cm* | *Objects 1-10 cm* | *Objects >10 cm* |
|---|---|---|---|
| | *Likely result of impact* | | |
| *Height of circular orbit* | *Possible loss of satellite* | *Probable loss of satellite* | *Fragmentation of satellite* |
| 500 km | 10-100 years | 3,500-7,000 years | 150,000 years |
| 1,000 km | 3-30 years | 700-1,400 years | 20,000 years |
| 1,500 km | 7-70 years | 1,000-2,000 years | 30,000 years |

Figure VIII
**Payloads and upper stages launched into geostationary orbit, 1963-1996**




88. There is no natural removal mechanism for satellites in GEO. Therefore, operational spacecraft are at risk of being damaged by uncontrolled spacecraft. This annual collision risk for an operational satellite is currently estimated at $10^{-5}$.

### 2.2.4 Risk assessments for re-entering space debris

89. The risk assessment discussed here is limited to uncontrolled re-entry from Earth orbit.

90. There have been more than 16,000 known re-entries of catalogued space objects in almost 40 years. No significant damage or injury has been reported. In large measure this can be attributed to the large expanse of ocean surface and the sparse population density in many land regions. In the past five years, approximately once each week, an object with a cross-section of 1 $m^2$ or more has re-entered Earth's atmosphere and some fragments have been known to survive.

91. The risk of re-entry is not only from mechanical impact, but also from chemical or radiological contamination to the environment. Mechanical damage will be caused by objects surviving aerodynamic heating. This risk will depend on the characteristics of the final orbit, the shape of the object and its material properties.

92. An assessment of re-entry risk must include the modelling of objects, analysis of the break-up altitude, identification of components that can survive re-entry and the calculation of total casualty area.

93. There is no international consensus on human casualties caused by re-entry. A casualty expectation of $10^{-4}$ per re-entry event is presented in NASA safety standard 1740.14, entitled "Guidelines and assessment procedures for limiting orbital debris".

# 3. Space debris mitigation measures

## 3.1 Reduction of the debris increase in time

### 3.1.1 Avoidance of debris generated under normal operation

#### 3.1.1.1 Mission-related objects

94. Approximately 12 per cent of the present catalogued orbital debris population consists of objects discarded during normal satellite deployment and operations. Typical objects in this category are fasteners, yaw and yo-yo weights, nozzle covers, lens caps, multiple payload mechanisms and so forth. It is normally relatively easy, both technically and economically, to take mitigation measures against these objects. Many agencies are reported to have taken such action. For example, clamp bands and sensor covers should be retained by parent bodies, and all fragments of explosive bolts should be captured. However, there may be some parts that will be released for unavoidable reasons, such as a structural element left in geostationary transfer orbit (GTO) during a multiple payload mission. Every agency is encouraged to minimize these kinds of debris whenever possible using state-of-the-art equipment or techniques.

#### 3.1.1.2 Tethers

95. Tethers may become orbital debris if they are discarded after use or if they are severed by an impacting object (man-made debris or meteoroid). Tethers several thousand metres in length and a few millimetres in diameter might not survive for extended periods. New multi-strand tether designs can reduce the risk of being severed. At the end of missions, tethers may be retracted to reduce the possibility of collision with other objects or both end masses may be released to accelerate the orbital decay of the tether.

#### 3.1.1.3 Solid rocket motor effluents, paint and other exterior materials

96. Other mission-related particles may be generated unintentionally, as in the release of slag (up to several centimetres in diameter) during and after the burn of solid rocket motors. The precise nature of the amount and distribution of these slag ejecta are unclear, and the improvement of solid propellant and motor insulation to minimize the released solids is difficult. Attempts should be made to inhibit the generation of very small debris caused by the effects of the space environment, for example, atomic oxygen erosion, solar radiation effects and the bombardment of small meteoroids. The application of more long-lasting paint and protective covering could be an effective remedial measure.

### 3.1.2 Prevention of on-orbit break-ups

97. The consequences of fragmentations of upper stages and spacecraft constitute approximately 43 per cent of the current identified satellite population and may account for as much as 85 per cent of all orbital debris larger than 5 cm in diameter. At least 153 space objects, with a total dry mass of more than 385,000 kg, are known to have broken up in Earth orbit as at 1 September 1998. Fortunately, 60 per cent of the catalogued debris generated in those events have fallen back to Earth. Such fragmentations are caused primarily by either explosions or collisions.

#### 3.1.2.1 On-orbit explosions

98. Thirty-six per cent of all resident space objects break-ups are upper stages or their components that operated successfully but were abandoned after the spacecraft delivery mission was completed. Such incidents have affected a wide range of launch vehicles operated by the United States, the Russian Federation, China and ESA. Accidental explosions can also be caused by malfunctioning propulsion systems, overcharged batteries or explosive charges. Intentional break-ups have also been conducted.

99. Analyses of accidental fragmentations for both spacecraft and upper stages have shown that vehicle deorbiting or passivation, i.e. the removal of all forms of stored energy, would eliminate most such events. Effective

measures include the expulsion of residual propellants by burning or venting, the discharge of electrical storage devices, the release of pressurized fluids, thermal control and safing of unused destruct devices and the unloading (despinning) of momentum wheels and similar attitude control apparatus. These measures should be performed soon after the vehicle has completed its mission.

#### 3.1.2.2 On-orbit collisions

100. The probability of an accidental collision in Earth orbit is currently slight, but it is becoming greater as the number and size of satellites are increasing. In 1996, the French CERISE spacecraft was struck and partially disabled by the impact of a fragment which, according to the United States Space Command monitoring network, came from an exploded Ariane upper stage. In addition, the possibility of other break-ups being caused by collision cannot be denied because the causes of many break-up events remain unknown. Effective measures to mitigate the consequences of break-ups caused by collision include the spacecraft design, selection of an orbit where the probability of collision is low, and collision avoidance manoeuvres (see paragraphs 112-118 below).

### 3.1.3 Deorbiting and reorbiting of space objects

#### 3.1.3.1 Mission termination of space systems

101. For space objects in LEO reaching end of mission, each vehicle should be deorbited or placed in a reduced lifetime orbit to reduce the possibility of an accidental collision. Studies have shown that the growth of orbital debris can be mitigated by limiting orbital lifetimes. This may be done with a controlled re-entry manoeuvre or by transferring the vehicle to a lower altitude.

102. For space objects at higher altitudes, moving vehicles into disposal orbits can also be effective for the foreseeable future. For example, the transfer of geostationary orbit spacecraft to orbits above GEO not only protects operational spacecraft but also reduces the probability of derelict objects colliding with one another and creating debris that might threaten the GEO regime. A standardized minimum reorbit distance value should be determined by taking into consideration factors such as perturbation effects by the gravitational force of the Sun and the Moon and solar radiation pressure. The upper stages or components of launch vehicles left in GTO may be manoeuvred to prevent interference with systems in GEO. The perigee altitude of the upper stage could be selected to ensure a limited orbital lifetime.

#### 3.1.3.2 In case of failure

103. Space systems on orbit should be continuously monitored especially for critical malfunctions that could lead to the generation of large amounts of fragments or to loss of the ability to conduct mitigation measures. The propulsion system, batteries and the attitude and orbit control subsystem should be monitored in that context. If a malfunction occurs and the mission cannot be maintained, procedures should be implemented to preclude accidental explosion and to prevent as much as possible interference with useful orbits.

## 3.2 Protection strategies

104. Given the current orbital debris population, spacecraft designers should consider incorporating implicit and explicit protection concepts into their space vehicles. A hazard for space objects and orbital stations is posed by hypervelocity impact with meteoroids and space debris particles 1-2 mm or larger. High-velocity impacts by particles as small as 1 mm in diameter can lead to loss of functions and potentially mission failure. Even small impacts on pressure vessels may result in container ruptures. Such damage may also prevent planned passivation measures or post-mission disposal options. In many cases, the relocation of vulnerable components can greatly increase spacecraft survivability. Prudent selection of the orbital regime and collision avoidance are other potential protection strategies.

### 3.2.1 Shielding

105. Orbital debris shields for both manned and unmanned spacecraft can be quite effective against small particles. Protection against particles 0.1-1 cm in size can be achieved by shielding spacecraft structures. All objects 1-10 cm in size cannot currently be dealt with by on-orbit shielding technology, nor can they be routinely tracked by operational surveillance networks. However, protection against particles 1-10 cm in size can be achieved through special features in the design of space systems (redundant subsystems, frangible structures, pressure vessel isolation capabilities, maximum physical separation of redundant components and paths of electrical and fluid lines etc.).

Physical protection against particles larger than 10 cm is not yet technically feasible.

106. Shielding designs may vary from simple single sheet Whipple bumpers, located in front of the spacecraft wall, to complex layers of metal and ceramic/polymer fabrics that are designed first to break up the impacting particle and then to absorb the energy of the resulting ejecta. Bumper shields should be positioned at sufficient distance from the shielded object to ensure a wide dispersion of the fragment cloud, created as a result of the impact of the debris particles on the shield. Thus, the impact loads should be distributed over a considerable area of the protected object's body. Successful shield designs may take advantage of the structure of the vehicle and the directionality of orbital debris to protect critical components. In addition, spacecraft can be designed to place critical components in the geometric shadow of the prevailing direction of debris flux. The application of lightweight, multilayer insulation may provide protection against small debris, and the placement of sensitive equipment behind existing vehicle structures may also improve survivability.

107. The penetration depth, or damage potential, of an impacting object depends on its mass, density, velocity and shape and on the material properties of the shield. Different modelling and simulation tools are available to predict the damage resulting from impacts on various shield designs (e.g. the NASA BUMPER model, the ESA ESABASE model, the Russian BUFFER model and several hydrocodes to perform simulations under conditions not possible using ground-based test facilities). Ground-based tests of spacecraft shields are limited, as testing for the entire range of possible impact velocities is not possible. Ground-based accelerators are currently limited to velocities of the order of 13 km/s (e.g. using shaped charge devices), but most existing data are for 7 km/s. New methods are being developed and further refined for calculating the processes involved in hypervelocity collisions between space debris particles and shields at impact velocities of 5-15 km/s.

#### 3.2.1.1 Human space flight

108. Manned spacecraft, particularly space stations, are normally larger than most unmanned vehicles and must demonstrate higher safety standards. Protection strategies for manned missions may incorporate both shielding measures and on-orbit repair of damage caused by penetrations. Current shield designs offer protection against objects smaller than 1 cm. The probability of no penetration (PNP) is the main criterion for shield design. PNP calculations are based on meteoroid and debris environment models and on the ballistic limit curves obtained in hydrocode simulations and hypervelocity impact experiments. The reliability of the PNP calculations is strongly linked to the accuracy of the debris and meteoroid environment model. The degree of shielding required is highly dependent upon the nature (material, thickness etc.), location and orientation of the surface to be protected. Consequently, the International Space Station will employ over 200 different types of orbital debris and micrometeoroid shields.

109. On manned spacecraft it is possible to install automatic detection systems to locate damage. In case of a puncture of a pressurized module, isolation of the module or reaction time in sealing the puncture is of primary importance. The amount of time available depends on the size of the puncture, and the time required for repair is a function of the means employed and the strategy adopted.

110. Crew members engaged in extravehicular activities (EVA) need protection from natural and man-made debris. Current spacesuits have many features with inherent shielding qualities to offer protection from objects of sizes up to 0.1 mm. By properly orienting their spacecraft, astronauts may be able to use their vehicles as shields against the majority of orbital debris or direct meteoroid streams.

#### 3.2.1.2 Unmanned spacecraft

111. For unmanned spacecraft, lower PNPs are tolerable. An acceptable level of protection against small debris and meteoroid objects (smaller than 1 mm) may be attained through the use of reinforced multilayer insulation materials and via design modifications, such as internal installation of fuel lines, cables and other sensitive components (for example, as implemented by RADARSAT of Canada). Solar array designs can minimize the effects of damage from collisions with small particles by using designs that have multiple electrical paths and that minimize structural mass, i.e. frangible configurations.

### 3.2.2 Collision avoidance

112. Current space surveillance systems do not reliably track objects in LEO with a radar cross-section of less than 10 cm in equivalent diameter. In addition, it is difficult to

maintain orbital parameters on small catalogue objects due to factors such as a high area-to-mass ratio and, consequently, a higher susceptibility to atmospheric density variations. For space objects large enough to be tracked by ground-based space surveillance systems, collision avoidance during orbital insertion and on-orbit operations is technically possible.

113. Collision avoidance manoeuvres impact satellite operations in several ways (e.g. propellant consumption, payload data and service interruptions, and temporary reduction in tracking and orbit determination accuracy), and they should be minimized, consistent with spacecraft safety and mission objectives. Collision avoidance strategies are most effective when the uncertainty in the close approach distance is kept small, preferably less than 1 km. Collision avoidance is always probabilistic. NASA uses an acceptable risk criterion of 1 in 100,000 to consider a collision avoidance manoeuvre for the United States Space Shuttle missions.

#### 3.2.2.1 On orbit

114. The United States Space Surveillance Network (SSN) and the Russian Space Surveillance System (SSS) monitor the LEO environment to warn crewed spacecraft if an object is projected to come within a few kilometres. For example, if an object is predicted to pass through a box measuring 5 km x 25 km x 5 km oriented along the flight path of the United States Space Shuttle, the SSN sensor network intensifies its tracking of the potential risk object. If the improved fly-by prediction indicates a conjunction within a box measuring 2 km x 5 km x 2 km, an avoidance manoeuvre may be performed. During the period 1986-1997, the United States Space Shuttle executed four such evasive manoeuvres. The Russian SSS performs similar collision avoidance assessments for the Mir space station.

115. Russian specialists have compiled a catalogue of dangerous approaches to space objects (several million approaches) and an algorithm for deciding whether to proceed with an avoidance manoeuvre. It is proposed to identify hazardous situations involving the predicted approach of space debris and to intensify data coverage of such events and flight control of the spacecraft requiring protection. Work is under way to establish a special telecommunication system linking RSA management with the mission control centre in Korolev.

116. ESA and CNES are using orbit determinations of their LEO spacecraft to forecast conjunction events and to initiate evasive manoeuvres if certain fly-by range limits or estimated collision risk levels are violated. For an accepted collision risk of 1 in 10,000, the ERS-1 and ERS-2 spacecraft of ESA would need to perform 1 or 2 manoeuvres each year. Collision avoidance manoeuvres were performed by the ESA satellite ERS-1 in June 1997 and by the CNES satellite SPOT-2 in July 1997.

117. As more spacecraft are launched into the GEO region, coordinated station-keeping is becoming increasingly beneficial. Inclination and eccentricity vector separation strategies can be efficiently employed to keep co-located GEO spacecraft at safe distances. Eccentricity vector control may also be employed to reduce the risk of collision between members of a given LEO satellite constellation.

#### 3.2.2.2 Launch

118. Calculations made prior to the launch of United States spacecraft permit the establishment of safe launch windows, ensuring that the spacecraft will not pass near resident manned spacecraft (i.e. Space Shuttle, Mir or the International Space Station). For the Space Shuttle, similar alert procedures are used as for the on-orbit conjunction analysis. In the case of a predicted conjunction, the launch is delayed; to date two Space Shuttle launches have been delayed to avoid potential collisions.

### 3.3 Effectiveness of debris mitigation measures

119. Probably one of the most important mitigation measures has been the increased awareness of the threats posed by the orbital debris environment and of the many sources of orbital debris. Incorporation of debris mitigation measures early in the vehicle design phase could be cost-effective. Educational efforts among the aerospace industries and national space agencies have reaped the rewards of voluntary action, guided by the principles of good stewardship of near-Earth space.

120. Since the early 1980s, the adoption of mitigation measures has had an effect on the growth of the orbital debris environment. The frequency of significant satellite fragmentations, both accidental and intentional, has dropped, moderating the rate of growth of orbital debris. For long-lived mission-related debris even a decrease is noticeable. New debris shield technologies and designs

have substantially reduced the weight of protection while increasing its effectiveness.

121. The aerospace community is working to illustrate the effectiveness and cost of typical mitigation scenarios. Long-term environment simulation models are useful in such work. The models cannot provide accurate predictions of the space environment several decades into the future, but they can evaluate the relative influences of different operational practices.

### 3.3.1 Scenarios of mitigation measures

122. Mission-related objects, satellite fragmentations and end-of-mission disposal practices are important factors in the potential growth of the orbital debris population. The five typical mitigation scenarios for all space missions presented below show the potential effectiveness of mitigation measures; they are not intended to be prescriptive in nature and should be used only for simulation purposes. The scenarios are the following:

(a) Reference scenario with current mitigation measures;

(b) Elimination of mission-related objects;

(c) Universal passivation at end of mission;

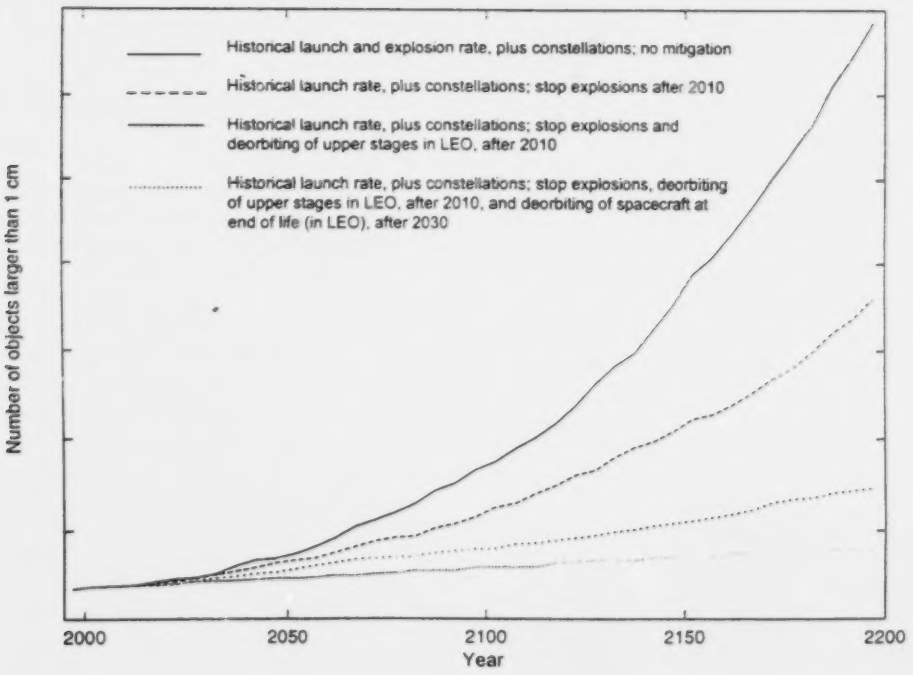
(d) Universal disposal at end of mission for GEO;

(e) Deorbiting at end of LEO and GTO mission: this includes both lowering the orbit to reduce the satellite lifetime (e.g. to less than 25 years) and immediate re-entry.

123. Initial studies have shown that the greatest near-term benefit can be gained by the elimination of accidental explosions of spacecraft and upper stages. Such break-ups are best controlled by the passivation of the vehicles at the end of mission, as demonstrated by many spacecraft and launch vehicle operators.

124. In the long term, the accumulation of objects in orbit may pose a significant increase of the threat to space operations in both low and high altitude regimes. Without

Figure IX
**Total population of debris particles larger than 1 centimetre in low Earth orbit for different scenarios, 2000-2200**


Historical launch and explosion rate, plus constellations; no mitigation
Historical launch rate, plus constellations; stop explosions after 2010
Historical launch rate, plus constellations; stop explosions and deorbiting of upper stages in LEO, after 2010
Historical launch rate, plus constellations; stop explosions, deorbiting of upper stages in LEO, after 2010, and deorbiting of spacecraft at end of life (in LEO), after 2030
Number of objects larger than 1 cm
2000
2050
2100
2150
2200
Year

remediation of the debris environment or operational changes, the growing number and total cross-section of resident space objects would increase the likelihood of collisions, which in turn could generate new debris. Placing LEO and GTO spacecraft into disposal orbits with limited orbital lifetime (e.g. 25 years or less) has a pronounced effect on curbing the growth of the debris population. Figure IX illustrates the total population of debris particles larger than 1 cm in LEO for a number of scenarios.

### 3.3.2 Cost or other impact of mitigation measures

125. Debris mitigation measures can affect the design and cost of spacecraft and launch vehicles as well as their operations.

#### 3.3.2.1 System development cost

126. Modifying the designs of spacecraft and launch vehicles to implement mitigation measures generally adds to the system development cost. However, allowing for mitigation measures early in the design process is more cost-effective than modifying a design later. Although increased vehicle complexity may arise, some mitigation measures may lead to simpler designs as well as weight savings.

#### 3.3.2.2 Launch performance and mass penalty

127. Providing for the upper stages of launch vehicles to re-enter the atmosphere directly or to have a short orbital lifetime may influence launch trajectory and performance. Likewise, any weight added to the launch vehicle or the spacecraft to meet mitigation objectives lowers the useful payload capacity. Additional propellant or electrical power resources may be needed. The magnitude of these consequences will vary depending upon the mitigation measure selected and the vehicle.

#### 3.3.2.3 Mission lifetime

128. For a given design, implementing disposal or deorbiting strategies may reduce the active mission lifetime. Many GEO spacecraft operators have accepted this penalty in order to preserve their orbital regimes. If the penalty is considered during the design process, full mission lifetime requirements can still be achieved, although at the potential expense of increased weight or cost.

#### 3.3.2.4 Reliability

129. Incorporating debris mitigation measures into spacecraft and upper stages may increase or decrease overall reliability. For example, shielding measures offer protection against small debris and radiation and may improve spacecraft reliability. The addition of relief valves to deplete residual propellants might decrease system reliability, but these effects are often quite small.

## 4. Summary

130. During its multi-year investigation of the space debris topic, the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space has examined: (a) the state of knowledge of the near-Earth debris population from both *in situ* and terrestrial-based sensors; (b) the capabilities of computer models to assess debris risks and to forecast the growth of space debris; and (c) a variety of space debris mitigation measures.

131. With the use of ground-based optical and radar surveillance systems around the world, space objects with diameters larger than 10 cm in LEO and larger than 1 m in GEO can be observed and tracked. More than 8,500 catalogued objects are in Earth orbit. The number of in-orbit catalogued objects has been increasing at a relatively linear rate for the past several decades.

132. Some nations have developed computer models of orbital debris based upon the large, catalogued population and upon statistical observations obtained by a wide variety of sensors. Despite the differences in the techniques applied in the models, the trends and tendencies predicted for the future orbital debris environment are qualitatively in agreement.

133. Of the debris mitigation measures identified, the limitation of mission-related debris and the prevention of accidental explosions have been found effective and have already been introduced to some extent. Also, the transfer of GEO spacecraft into disposal orbits at the end of their active life is already customary practice, followed as an intermediate measure to prevent future problems in GEO. IADC has suggested an algorithm for the determination of the minimum altitude of the disposal orbit above GEO. For some satellites on long lifetime LEO orbits, a transfer to shorter lifetime orbits is planned at the end of their active

life. Such procedures, in general, would be most effective in limiting the density of objects in those altitude bands that are most highly populated at present. Since most of the mitigation measures introduce some cost burden to missions, it is essential that the same debris avoidance procedures are applied globally.

134. Many organizations involved in space operations have become aware of the potential threats of space debris, and some of those organizations have initiated efforts to mitigate debris generation and to share the results of those efforts with the international community. The activities of international organizations such as IADC and IAA have made positive contributions to space debris research and education. IADC members represent essentially all of the nations with launching capabilities and those that design and build the majority of space systems.

135. In most cases, man-made space debris today poses little risk to the successful operations of approximately 600 active spacecraft now in Earth orbit. However, the known and assessed population of debris is growing, and the probabilities of potentially damaging collisions will consequently increase. Because of the difficulty of improving the space environment with existing technologies, the implementation of some debris mitigation measures today is a prudent step towards preserving space for future generations. In some cases, technical work remains to be done to determine the most effective and cost-efficient solutions.

*Notes*

[1]The Subcommittee at its thirty-sixth session will have before it the latest document containing such information (A/AC.105/708).

# Annex

## List of documents relevant to the subject "Space debris"

### Reports on sessions of the Scientific and Technical Subcommittee

Report of the Scientific and Technical Subcommittee on the work of its thirty-first session (A/AC.105/571, 10 March 1994)

Report of the Scientific and Technical Subcommittee on the work of its thirty-second session (A/AC.105/605, 24 February 1995)

Report of the Scientific and Technical Subcommittee on the work of its thirty-third session (A/AC.105/637 and Corr. 1, 4 March 1996)

Report of the Scientific and Technical Subcommittee on the work of its thirty-fourth session (A/AC.105/672, 10 March 1997)

Report of the Scientific and Technical Subcommittee on the work of its thirty-fifth session (A/AC.105/697 and Corr.1, 25 February 1998)

### Reports on national research on space debris

Use of nuclear power sources in outer space (A/AC.105/C.1/WG.5/L.24, 15 January 1990)

Use of nuclear power sources in outer space (A/AC.105/C.1/WG.5/L.24/Add.1, 14 February 1990)

Use of nuclear power sources in outer space (A/AC.105/C.1/WG.5/L.24/Add.2, 26 February 1990)

Use of nuclear power sources in outer space (A/AC.105/C.1/WG.5/L.24/Add.3, 28 February 1990)

Space debris: status of work in Germany: working paper by Germany (A/AC.105/C.1/L.170, 12 February 1991)

National research on the question of space debris (A/AC.105/510, 20 February 1992)

National research on the question of space debris (A/AC.105/510/Add.1, 21 February 1992)

National research on the question of space debris (A/AC.105/510/Add.2, 26 February 1992)

National research on the question of space debris (A/AC.105/510/Add.3, 26 February 1992)

National research on space debris; safety of nuclear-power satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/542, 8 February 1993)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/542/Add.1, 17 February 1993)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/542/Add.2, 19 February 1993)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/565 and Corr.1, 16 December 1993)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/565/Add.1, 21 February 1994)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/565/Add.2, 23 February 1994)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/593, 1 December 1994)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/593/Add.1, 24 January 1995)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/593/Add.2, 6 February 1995)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/593/Add.3, 7 February 1995)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear

power sources with space debris (A/AC.105/593/Add.4, 24 February 1995)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear-powered sources with space debris (A/AC.105/619, 21 November 1995)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear-powered sources with space debris (A/AC.105/619/Add.1, 1 February 1996)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear-powered sources with space debris (A/AC.105/659, 13 December February 1996)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear-powered sources with space debris (A/AC.105/659/Add.1, 6 February 1997)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear-powered sources with space debris (A/AC.105/659/Add.2, 14 February 1997)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear-powered sources with space debris (A/AC.105/680 1 December 1997)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear-powered sources with space debris (A/AC.105/680/Add.1, 2 February 1998)

## Documents on mitigation steps taken by space agencies

Steps taken by space agencies for reducing the growth or damage potential of space debris (A/AC.105/620, 21 November 1995)

Steps taken by space agencies for reducing the growth or damage potential of space debris (A/AC.105/663, 13 December 1996)

Steps taken by space agencies for reducing the growth or damage potential of space debris (A/AC.105/681, 17 December 1997)

## Scientific and technical presentations

Scientific and technical presentations to the Scientific and Technical Subcommittee (A/AC.105/487, 9 May 1991)

Scientific and technical presentations to the Scientific and Technical Subcommittee (A/AC.105/516, 29 May 1992)

Scientific and technical presentations to the Scientific and Technical Subcommittee (A/AC.105/546, 18 May 1993)

Scientific and technical presentations to the Scientific and Technical Subcommittee at its thirty-first session (A/AC.105/574, 12 May 1994)

Scientific and technical presentations to the scientific and technical subcommittee at its thirty-second session (A/AC.105/606, 27 April 1995)

Scientific and technical presentations to the scientific and technical subcommittee at its thirty-third session (A/AC.105/638, 7 May 1996)

Scientific and technical presentations to the scientific and technical subcommittee at its thirty-fourth session (A/AC.105/673, 7 May 1997)

Scientific and technical presentations to the scientific and technical subcommittee at its thirty-fifth session (A/AC.105/699, 20 April 1998)

## Working papers and reports

Space debris: a status report submitted by the Committee on Space Research (A/AC.105/403, 6 January 1988)

Environmental Effects of Space Activities: report submitted by the Committee on Space Research and the International Astronautical Federation (A/AC.105/420, 15 December 1988)

The problem of space debris: working paper submitted by Australia, Belgium, Canada, the Federal Republic of Germany, the Netherlands, Nigeria and Sweden (A/AC.105/L.179, 1 June 1989)

Use of nuclear power sources in outer space; space debris: working document submitted by the Russian Federation (A/AC.105/C.1/L.193, 21 February 1994)

Space debris: report of the International Astronautical Federation (A/AC.105/570, 25 February 1994)

Collisions between nuclear power sources and space debris: working paper submitted by the Russian Federation (A/AC.105/C.1/L.204, 13 February 1996)

Brief review of the work done by Russian scientists on the problem of the technogenic pollution of near space: working paper submitted by the Russian Federation (A/AC.105/C.1/L.205, 13 February 1996)

Space debris: working paper submitted by the International Academy of Astronautics (A/AC.105/C.1/L.217, 12 January 1998)

Space debris: working paper submitted by the Russian Federation (A/AC.105/C.1/L.219, 10 February 1998)

## Revisions to the technical report

Revisions to the technical report on space debris of the Scientific and Technical Subcommittee (A/AC.105/C.1/L.214, 26 February 1997)

Revisions to the technical report on space debris of the Scientific and Technical Subcommittee (A/AC.105/C.1/L.224, 19 February 1998)

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**Committee on the Peaceful Uses of Outer Space**

# National research on space debris, safety of nuclear-powered satellites and problems of collisions of nuclear-powered sources with space debris

**Note by the Secretariat**

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## I. Introduction

1. In its resolution 52/56, paragraph 29, of 10 December 1997, the General Assembly considered it essential that Member States pay more attention to the problem of collisions of space objects, including those with nuclear power sources, with space debris, and other aspects of space debris, and called for the continuation of national research on that question, for the development of improved technology for the monitoring of space debris and for the compilation and dissemination of data on space debris. To the extent possible, the Assembly considered that information thereon should be provided to the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space.

2. The General Assembly, in paragraph 18 of the same resolution, invited Member States to report to the Secretary-General on a regular basis with regard to national and international research concerning the safety of space objects with nuclear power sources on board.

3. The Secretary-General addressed a note verbale, dated 17 July 1998, to all Member States, inviting them to communicate to the Secretariat, by 30 September 1998, the information requested above, so that the Secretariat could prepare a report containing that information for submission to the Subcommittee at its thirty-sixth session.

V.98-58036 (E)

4. The present document was prepared by the Secretariat on the basis of information received from Member States and international organizations as of 1 December 1998. Information received subsequent to that date will be included in addenda to the present document.

# II. Replies received from Member States*

## Canada

Canada attaches considerable importance to the issue of space debris. However, given that the scope of activity in space debris is beyond the capabilities of Canada, the country has chosen to focus its research and analysis efforts. Two areas of interest, in which work is advancing, include debris monitoring and damage avoidance.

In the area of debris monitoring, Canada led an international team in 1997 to measure the Leonid meteorite flux. After a successful campaign and instrumentation verifications, plans are now taking shape for Canada to lead a much larger and more integrated campaign for Leonids 98. Although not specifically part of the orbital debris population, the meteoroid population constitutes a significant segment of the mass distribution of incoming particles for which protective measures must be provided. The primary optical observation will be located in Outer Mongolia, with a secondary optical and microwave sensing location in northern Australia. Real-time data links to North American sites are planned so as to provide data to commercial operators. The forthcoming Leonid shower is expected to be the largest experienced to date, since significant space assets have been placed in orbit.

Damage protection and avoidance work on composite structures such as the Multi-spectral Scanner are continuing with the use of hyperactivity in the United States of America and the United Kingdom of Great Britain and Northern Ireland. The aim of these studies is to develop better protection techniques for future hardware.

## United Kingdom of Great Britain and Northern Ireland

The United Kingdom continues to play a key role in dealing with the space-debris problem. It has a wide-ranging research programme looking at important aspects of debris and participates fully at national level through a United Kingdom Co-ordination Group, at European level through the European Space Agency (ESA), and at international level within the Inter-Agency Debris Co-ordination Committee (IADC) and the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS). The programmes are coordinated by the British National Space Centre (BNSC).

BNSC co-sponsored a workshop on space hazards hosted by the United Kingdom Defence Evaluation and Research Agency (DERA) at Farnborough on 21 and 22 October 1998. This involved leading researchers in the debris field from Europe and addressed issues such as basic research into space debris, through the development of models, to final exploitation by industry of guidelines.

A United Kingdom coordination meeting took place on 29 January 1998 at the Royal Greenwich Observatory (RGO), Herstmonceux Castle, involving: Advanced System Architectures, BNSC, Century Dynamics, DERA, Fluid Gravity Engineering, the Ministry of Defence, Matra Marconi Space, RGO and the universities of Cranfield, Kent, London and Southampton. Presentations were given on a diverse range of subjects covering: activities at the previous IADC meeting in Houston, Texas; progress in developing debris-tracking equipment; advances in, and results from, new debris/meteoroid models; and research activities relating to debris shielding.

The United Kingdom participated fully within IADC at meetings in Houston during December 1997 and at a Steering Group meeting in Nagoya, Japan, on 15 July 1998.

The studies and resulting publications derived from United Kingdom organizations involved in debris research are given below.

* The replies are reproduced in the form in which they were received.

### A. University of Kent

The University of Kent, through the Unit for Space Sciences, provides a major contribution in all aspects of space-debris research. A high profile is maintained through attendance at a number of major international forums, including: the thirty-second Scientific Assembly of the Committee on Space Research (COSPAR),[1, 2, 3, 4] and the Hypervelocity Impact Symposium 1998.[5, 6] Research activities continue to focus on: the design and development of *in situ* debris detectors; analysis of impact results from detectors and retrieved spacecraft surfaces; and characterization of composite spacecraft materials under hypervelocity impact conditions. Each of these is discussed in more detail below.

*Debris detectors*. Progress on three flight opportunities has been maintained, and space instrumentation developed, through the production of a compact and cost-effective space sensor, DEBIE. A Finnish consortium is assisting in one of these opportunities, providing for manufacture in readiness for flight in 2000 on ESA's PROBA launch. Tests at Kent on a 2 MV microparticle accelerator have established impact plasma yields, design data, and data rates, thus enabling optimization of costs and data-handling. This flight opportunity also provides for data analysis at Kent. On the second opportunity, the STRV 1C satellite, Kent's development and test programme has established a schedule with October 1998 flight unit hardware. The flight—now scheduled for August 1999—will be in time for the advent of the Leonids Meteoroid shower in November 1999. Selected for a flight opportunity in the International Space Station arena, the third opportunity for DEBIE's flight will provide for directional information of microdebris flux and meteoroids in the vicinity of large space structures.

*Analysis of retrieved surfaces*. The solar array returned to Earth from the Hubble Space Telescope (HST) in 1993, after 3.62 years of space exposure at approximately 600 km altitude, and continues to offer an opportunity to document further the constitution of space debris and micrometeoroids in low Earth orbit. Hypervelocity impact into space hardware of particles from either of these populations leave little evidence of the original impactor, and so defining the original nature of the impactor is difficult. However, recent work to re-evaluate the HST solar cells, by employing analytical electron microscopy techniques, has achieved some success in this regard. This research has highlighted that post-flight investigations of space-exposed hardware can yield much valuable information on the debris population. As a consequence, Kent (under contract to ESA) has derived updated debris fluxes at low Earth altitudes for space debris models of the National Aeronautics and Space Administration (NASA).

*Impact characterization of composite materials*. In addition to characterizing the debris environment, Kent has also been active in determining the consequences of hypervelocity debris impacts on spacecraft structural materials. Typically, these materials comprise aluminium or woven composite material face-sheets. For the majority of spacecraft in low Earth orbit, they provide the primary shielding protection against space debris and meteoroid particle impact. Results of an impact test programme using Kent's two-stage light gas gun showed that the threshold for perforation of the chosen composite targets was strongly dependent on impact angle. The next phase in the research will concentrate on the construction of a ballistic limit equation, which will be a valuable additional piece of information to aid in the satellite structure design process.

### B. University of London

The University of London debris research team at Queen Mary and Westfield College are developing models to represent the sources of microdebris encountered in space. This modelling work is complementary to that of the University of Kent. A series of empirical models are being developed to identify the amount of microdebris deposited into space as a function of orbital altitude and inclination, duration in orbit, spacecraft surface materials and the external space environment that was encountered.

This work is supported by research into novel techniques for representing the collision dynamics and frequency for different populations of objects in orbit. One of the most promising approaches is that of Direct Simulation Monte Carlo,[7] which uses techniques derived from rarefied gas computations. The evolved environment predicted by this model approach and the flux observed on the Long Duration Exposure Facility for small impactors show good agreement. More recently, the model has been used to provide a statistical uncertainty analysis to improve debris impact risk assessments of Space Shuttle windows.[8] The software predicts that for the majority of Shuttle flights between 0 and 2 windows will need replacing as a result of debris impact.

### C. University of Southampton

The University of Southampton continues to concentrate on collision events and risk analysis over a shorter time-frame. A set of modelling programs called the Space Debris Simulation suite considers the consequences of collision- or explosion-induced break-ups and the short-term evolution of the resulting debris cloud. Using a generalized approach to the method of probabilistic continuum dynamics, the software is able to follow the trajectories of the resulting fragments to determine the likelihood of collision with other objects, and if a collision were to occur, the level of damage that might be expected. Recently, the model has been used to carry out an analysis of the break-up of an object in the proximity of the International Space Station, and assess the probability of a damaging impact. This work is being reported at the forty-ninth International Astronautical Congress (a major international forum widely attended by the space community).

### D. Matra Marconi Space

United Kingdom indutry continues to recognize the deleterious effects of the space debris environment on satellites. Matra Marconi Space is leading a consortium comprising the University of Kent and DERA to research improved methods for implementing cost-effective shielding on unmanned spacecraft. The work has resulted in the construction of two baseline shield designs,[9] which will be impact-tested using the University of Kent light gas gun. Results from the tests will establish the effectiveness of different shield configurations for debris penetration resistance. Ultimately, this will ensure that United Kingdom and European satellite manufacturers can adopt the most robust and economic debris protection in the design of future satellites.

### E. Century Dynamics

Century Dynamics maintain their unique capability to investigate the processes of hypervelocity impacts through continued development of the AUTODYN-2D™ hydrocode. In conjunction with the Unit for Space Sciences at the University of Kent, they have completed a programme of simulations to investigate the response of brittle materials to a range of hypervelocity impact conditions.[10] This work is very important because it allows a comparison to be made to assess the accuracy of the hydrocode simulation results, and also provides a tool with which the designer can begin to investigate the response of characteristic spacecraft materials to impact by debris and meteoroids.

Century Dynamics continue to address the computer-intensive nature of hydrocode modelling by assessing the correct balance between speed and accuracy. As part of this process, they have collaborated with DERA to implement new techniques, such as Smooth Particle Hydrodynamics,[11] in their models. Finally, Century Dynamics are at the forefront of development of material models for strong, lightweight materials such as Nextel and Kevlar.[12] These materials are being increasingly used in spacecraft designs, particularly for debris-shielding, and so it is important to understand their impact characteristics through this work.

### F. Defence Evaluation and Research Agency

DERA is responsible for the technical coordination of the United Kingdom's space-debris research programme. In addition, the Agency is developing a number of software analysis tools.

The first is a suite of software called Integrated Debris Evolution Suite (IDES),[13] which is able to provide an assessment of the future collision risk that will be encountered by spacecraft. The software is able to model all launch and orbital activity, including collisions, explosions, separations and shedding. It is also able to propagate the orbits of the objects introduced into the space environment and consider the influence of gravitational perturbations, atmospheric drag and the influence of the Sun and Moon. A comprehensive testing programme has been carried out to ensure that the predictions agree well with observations. Using a combination of radar tracking data for larger objects and retrieved surface analysis for smaller objects, good correlation is found between predictions and observations. This validation process is an ongoing task, as the space-debris environment is highly dynamic in nature.

The confidence derived from good comparison with actual data to date has encouraged the users of IDES to use it in predictive mode. This has enabled the impact of future planned systems to be determined. The influence of low-Earth-orbit satellite communication systems (constellations) on the growth of debris in orbit continues to be investigated through a series of studies.[14] It has been demonstrated that the coupling between the large number of new satellites and the background debris population will significantly increase the growth rate of objects in orbit. It is also clear that the constellation satellites themselves will

be more susceptible to collisions. The effect of introducing debris-mitigation measures, such as de-orbiting of satellites at end of life, is also being studied.[15] The mitigation scenarios currently proposed appear to offer only a partial solution to the growth of the debris environment and the associated satellite collision risk.

Complementary to this environment modelling tool, a risk/design tool called PLATFORM is being developed to synthesize the debris population data predicted by IDES and determine the distribution of debris impacts on a target satellite as it orbits through the environment. From this impact data, and knowing the configuration of the target satellite, PLATFORM is able to calculate the survivability of the satellite. The PLATFORM model is linked to a novel module termed SHIELD,[16] which is being designed to identify the optimum choice of shielding and configuration of individual elements of a satellite. The optimization process uses a genetic algorithm, which is ideally suited to the consideration of design constraints such as maintaining the satellite's mass and thermal balance. The combination of IDES and PLATFORM/SHIELD represents a powerful tool for designing satellites to meet future technological challenges posed by space debris.

*Notes*

[1] G. A. Graham and others, "The collection of micrometeoroid remnants from low Earth orbit", presented at the thirty-second COSPAR Scientific Assembly, held in Nagoya, Japan, in July 1998.

[2] J.A.M. McDonnell and others, "APSIS—Aerogel position-sensitive impact sensor; Capabilities for *in situ* collection and sample return", presented at the thirty-second COSPAR Scientific Assembly, held in Nagoya, Japan, in July 1998.

[3] J.A.M. McDonnell, N. McBride and S. F. Green, "Meteoroids and small-size debris in LEO and at 1AU: results of recent modelling", presented at the thirty-second COSPAR Scientific Assembly, held in Nagoya, Japan, in July 1998.

[4] E. A. Taylor and others, "Space debris impacts on HST and Eureca solar arrays compared with LDEF using a new glass-to-aluminium conversion", presented at the thirty-second COSPAR Scientific Assembly, held in Nagoya, Japan, in July 1998.

[5] G. A. Graham and others, "Natural and simulated hypervelocity impacts in solar cells", presented at the Hypervelocity Impact Symposium, held in Huntsville, Alabama, United States of America, in November 1998.

[6] E. A. Taylor, M. K. Herbert and J.A.M. McDonnell, "Hypervelocity impact on carbon-fibre-reinforced plastic/aluminium honeycomb: comparison with Whipple bumper shields", presented at the Hypervelocity Impact Symposium, held in Huntsville, Alabama, United States, in November 1998.

[7] L. Wang and J.P.W. Stark, "Direct simulation of space debris evolution", to be published in the *Journal of Spacecraft and Rockets*.

[8] L. Wang and J.P.W. Stark, "Direct simulation of space shuttle space-debris flight damage", paper No. IAA-98-IAA.6.4.02, presented at the forty-ninth International Astronautical Congress, held in Melbourne, Australia, in September/October 1998.

[9] J. E. Wilkinson, P. H. Stokes, G. G. Swinerd and R. Walker, "Implementation of a new approach to optimise satellite debris protection", presented at the twenty-first International Symposium on Space Technology and Science, held in Omiya, Japan, in May 1998.

[10] E. A. Taylor and others, "Hydrocode modelling of hypervelocity impact on brittle materials: depth of penetration and conchoidal diameter", presented at the Hypervelocity Impact Symposium, held in Huntsville, Alabama, United States, in November 1998.

[11] C. J. Hayhurst and others, "Numerical simulation of hypervelocity impacts on aluminium and Nextel/Kevlar Whipple shields", presented at the Hypervelocity Shielding Workshop, held in Galveston, Texas, United States, in March 1998.

[12] C. J. Hayhurst and others, "Development of material models for Nextel and Kevlar-epoxy for high pressures and strain rates", presented at the Hypervelocity Impact Symposium, held in Huntsville, Alabama, United States, in November 1998.

[13] R. Walker, P. H. Stokes, J. Wilkinson and G. G. Swinerd, "Enhancement and validation of the IDES orbital debris environment model", submitted to the *Space Debris* journal for publication in the first issue (February 1999).

[14] R. Walker, R. Crowther, J. Wilkinson, P. H. Stokes and G. G. Swinerd, "Orbital debris collision risks to satellite constellations", presented at the IAF International Workshop on the Mission Design and Implementation of Satellite Constellations, held in Toulouse, France, in November 1997.

[15] R. Walker, R. Crowther, M. Cosby, P. H. Stokes and G. G. Swinerd, "The long-term impact of constellations on the debris environment after the implementation of debris mitigation measures", presented at the forty-eighth International Astronautical Congress, held in Turin, Italy, in October 1997.

[16] P. H. Stokes, R. Walker, J. E. Wilkinson and G. G. Swinerd, "Novel modelling solutions for debris risk reduction", presented at the thirty-second COSPAR Scientific Assembly, held in Nagoya, Japan, in July 1998.

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# National research on space debris, safety of nuclear-powered satellites and problems of collisions of nuclear-powered sources with space debris

**Note by the Secretariat**

**Addendum**

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## I. Introduction

1. The Secretary-General, in a note verbale dated 17 July 1998, invited all Member States to provide information on national research on space debris, safety of nuclear-powered satellites and problems of collisions of nuclear-powered sources with space debris.

2. The present document contains information provided in replies received from Member States between 1 December 1998 and 30 January 1999.

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# II. Replies received from Member States*

## Italy

[Original: English]

### 1. Introduction

1. Outer space has become an essential resource for scientific research and for application development in the public and private sectors. Projects for the installation and use of space systems, including large-scale manned missions, are constantly being developed. Nevertheless, these activities are subject to growing risk owing to the uncontrolled production of orbiting debris. During the early 1960s, when manned orbital flights first started, micrometeorites presented the only danger of satellite collision, with a very low rate of collision probability. Today the greatest danger is caused by artificial objects, mainly metallic ones produced during space flights, including:

(a) Spacecraft at the end of their operational life, which are particularly dangerous when they contain radioactive material;

(b) Fragments of satellites that have partially or completely exploded, components from the separation of stages and the separation of stages and satellites;

(c) Fragments of solar panels;

(d) Spent rocket bodies, including the apogee motors;

(e) Fragments of pressurized tanks that have exploded for various reasons.

2. Because of their amount, size and kinetic energy, such debris are an ever increasing and significant danger. Fragments above 1 mm in size are especially worrying. Debris are found mainly in low Earth orbits (below 1,500 km); they have a high relative velocity, are hard to detect with radar technology and optical methods, and have a long orbital life. The research group of the Institute of the National Research Council (CNR) at Pisa (CNUCE) has shown that the new debris created by collisions with orbiting objects may create a chain reaction, which in the long term could even prevent space activity at low Earth orbits.

3. The organizations involved in the planning and regulation of space activities have begun to address the problem and have issued numerous warnings. They have, however, come up against many difficulties in reaching international agreement in a sector with substantial commercial interests. As in other cases of technology assessment, where long-term evaluation of technological progress is required, decisions must be taken despite considerable ignorance regarding medium- and long-term risks. The classical approach of short-term profit, rejecting limitations not based on certain forecasts, can no longer be sustained. Feasible strategies involve long-term delays before achieving results and significant rigidity in the development of new technology, also because of the large capital resources required. On the other hand, they should be flexible and open to constant updating in order to ensure long-term protection for space activities in a framework of continually evolving knowledge.

* The replies are reproduced in the form in which they were received.

4. The awareness of the risks already present for space missions is reflected in the setting up of international committees for the coordination of space debris-related activity, in particular the Inter-Agency Space Debris Coordination Committee (IADC), and in the introduction of the problem in the agenda of the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space in 1994. Technical and legal organizations have formally expressed their position on the matter, focusing above all on the need for concrete measures. The organizations include the American Institute of Aeronautics and Astronautics (AIAA), the Committee on Space Research (COSPAR), the International Academy of Astronautics (IAA), the International Astronautical Federation (IAF), the International Institute of Space Law (IISL) and the International Law Association (ILA).

5. The Italian delegation at the Scientific and Technical Subcommittee has expressed satisfaction with the consideration of the problem. The position of the Italian delegation encourages discussion on the legal and political aspects of the problem. Italy also confirms its support, at the international level and in the appropriate bodies, for all the initiatives aimed at accelerating the acquisition of technology required to draw up programmes for concrete intervention.

## 2. Italian Space Agency

6. Since the 1980s, the Italian Space Agency (ASI) has devoted attention to the problem of space debris, at the time mainly focused on uncontrolled re-entry into the atmosphere of hazardous space objects. The 1988 re-entry in the atmosphere of the Soviet Cosmos 1900 satellite, carrying nuclear material on board, was an important occasion for ASI activity related to space debris. In parallel, the Italian Department of Civil Defense established a permanent committee to advise on emergencies that were due to re-entries of large space objects; several public administrations are represented on the committee, including the Italian National Agency for Nuclear and Alternative Energy (ENEA) for possible nuclear risks. ASI, with the support of CNUCE, participates in this committee for technical aspects (monitoring, re-entry predictions etc.). CNUCE technical support to ASI is managed under an agreement between ASI and CNR.

7. ASI also takes part in European Space Agency (ESA) activities and in the Italian delegation to the two subcommittees of the Committee on the Peaceful Uses of Outer Space. The most important international responsibility of ASI, however, is its membership in IADC. ASI was admitted as the tenth member in July 1998 and has already made relevant contributions to the activities of IADC at its general assembly in Toulouse, held from 2 to 6 November 1998.

8. The interest of ASI in the problem of space debris led to the establishment, in February 1995, of a Space Debris Working Group, which carried out a survey of the space debris activities in Italy and proposed some guidelines for future work. In its final report (June 1996), the Group reviewed the major aspects of this problem and the results obtained and proposed a three-year plan of research to be conducted in Italy. The international juridical framework has also been surveyed.

9. ASI has supported several research projects in the field of space debris, in particular, a recent study for a space system to take a spacecraft out of orbit at the end of its life by means of long conducting wires.

### 3. Institute of the National Research Council at Pisa

#### Activities

10. The traditional role of CNUCE in the field of celestial mechanics and space flight dynamics has naturally resulted in the commitment of CNUCE in the related field of space debris. Since 1979 when the Skylab re-entered the atmosphere, the Institute has dealt with the determination of the orbital evolution and prediction of re-entries of potentially dangerous and uncontrolled space objects. The Institute has direct contacts with national authorities, which have gradually taken on responsibilities for emergencies in this field, as well as foreign organizations in Europe, Japan, Russia and the United States involved in related tasks.

11. During recent years, besides taking part in a dozen re-entry campaigns, CNUCE has actively collaborated with the Civil Defense Department and the Data Evaluation Center for the management of nuclear emergencies, including those arising from spacecraft re-entry, especially with regard to the production of manuals and procedures. This technical and organizational work has led to the consolidation of duties, responsibilities and procedures on the national level, with a great improvement both in the interface with all the other organizations concerned and in their operational readiness.

12. After the establishment of ASI in 1988, the traditional activity of CNUCE in the field of re-entries and space debris expanded in the broader context of national space activities and the collaboration between government organizations and civil defence institutions. The Space Objects Monitoring Service (SMOS) was set up at Pisa, partially implementing the proposals made by the specialized working group set up by the former Ministry for Civil Defense in which ASI and CNUCE representatives also took part.

13. When problems related to the overcrowding of circum-terrestrial space owing to man-made space debris came to the fore, CNUCE/SMOS, in collaboration with the Space Mechanics Group of the Department of Mathematics of the University of Pisa, began studying increasingly sophisticated mathematical models for the long-term evolution of the debris population. The two final models were produced under an ESA contract, which extended from 1992 to 1996, and are briefly described in a subsequent section.

14. The activities of SMOS, besides forecasting the uncontrolled re-entry of potentially dangerous space objects, also involve regular monitoring of international space activities and location in Earth orbit, development, improvement and implementation of application software, issuing of reports, technical support for ASI in the space debris field, study of the long-term evolution of the orbiting debris population and evaluation of the effectiveness of mitigation measures.

#### Software development

15. The future evolution of the debris population in Earth orbit depends on many variables, some of which are under human control (the number and type of launches, measures for preventing explosion collision events etc.), while others are more specifically physical (mass distribution and velocity of fragments deriving from explosions or collisions, resistance to impact of other objects, collision probability and impact velocity for different orbits, effect of atmospheric drag on the re-entry of objects of different shapes, sizes and altitudes). A quantitative study of the problem requires the development of rather complex models and algorithms in order to provide realistic simulations and

sufficient flexibility to allow for the investigation of many alternative scenarios, with suitable options or numerical parameters to be chosen as inputs for the simulations.

16. Such research has grown significantly in Italy over the past 10 years. An initial, simple mathematical model, based on a system of just two differential equations, proved suitable to illustrate the mechanism that can ultimately lead to a chain reaction of orbiting debris. A realistic numerical model was later developed on the basis of an accurate estimate of collision probability as a function of altitude and quantitative description of the "sink" and "source" mechanisms (air drag, launches, explosions, collisions), which increase or decrease the debris population. These processes have been modelled mathematically with a system of 150 differential equations for the Earth orbiting objects, divided into 15 altitude shells and 10 mass bins (each differing in mass by factor 10 from the previous one, from one milligram to 10 tons). This model has confirmed both the danger of a chain reaction and the fact that the related time of occurrence depends on the parameters, especially the resistance of larger bodies to collisional destruction.

17. A further research phase was carried out between 1993 and 1995 at the Pisa-based CNUCE in the context of an ESA/ESOC contract with the Consorzio Pisa Ricerche (Pisa Research Consortium). Its purpose was to develop physical models, mathematical algorithms and numerical codes for the analysis of long-term evolution of the space debris population in Earth orbit. The project focused on development, implementation on UNIX workstations, validation and use of three numerical codes and the corresponding pre- and post-processing programs.

18. The contract also required a variety of highly specialized support activities, including the following: detailed study of past and future traffic models (launches, satellite constellations, space stations, military and commercial requirements); identification of the physical characteristics and the type of utilization of all carrier rockets now in use or to be used; development of atmospheric density models, also taking into account the solar flux variations; development of a sufficiently accurate and fast orbital propagator designed to survey thousands of objects at the same time; study and assessment of different models to describe fragmentation events (high and low energy explosions and collisions); and simulation of the current space debris population (produced by launches, decays and past fragmentations) for masses exceeding one milligram.

### 4. Protecting space vehicles

19. Space engineers must carefully take into account the risk to operational space structures of collisions with potentially damaging space trash. At an impact velocity of about 10 km/s, the impact pressure reaches values up to some Mbar; the interaction is dominated by the shock pressure; the material is subject to solid-liquid-vapour phase transitions. Orbital debris pose a particularly severe threat to the International Space Station, because of its large dimensions (more than 11,000 $m^2$ of surface area), its long operational life (greater than 10 years) and the permanent presence of human beings on board. The evaluation of the potential hazards of debris impact shows the need for the space station modules to be protected with special shields.

20. Italy has carried out relevant activities in this area. At the Center of Studies and Activities for Space of the University of Padova, a gas gun has been designed and built to accelerate small metal projectiles to high velocities. It works with pressurized helium in two stages, with a maximum pressure and peak temperature in the second stage of 6,000 bar and 5,000 degrees, respectively. Accurate diagnostics allow monitoring of all

stages of acceleration and a duty cycle up to one shot per minute. Masses of 0.5 and 2.5 are accelerated, respectively, to 6 and 2.1 km/s. Although they are lower than the typical debris velocities, the impacts they produce have the same physical structure and effects and are quite useful in understanding the complex and fast phenomena in hypervelocity collisions, which include shock waves, melting and vaporization, fragmentation, ejection of fragments in different directions, and fast heating and fast cooling both for the target and the projectile. The gun is also useful as a prototype for a larger machine, capable of attaining larger velocities.

21. Although the microscopic phenomena involved are essentially known, the physics of hypervelocity collisions is far too complex to be amenable to analytical treatment: complex computer codes are needed to describe their effects on a metal layer and on a multilayer shield. Advanced codes of this kind, based on the smoothed particle hydrodynamics (SPH) technique, have been implemented and are being currently used at the University of Rome "La Sapienza". SPH codes, originally developed for astrophysics, describe the evolution of the medium by means of extended "particles" whose motion and properties are measured over a period of time.

22. Alenia Aerospazio in Turin is responsible for the structural design and manufacturing of several modules of the International Space Station. Protecting shields are carefully designed and evaluated for each one of them. The shielding strongly affects the overall design, with a mass increase that can be as high as 1.5 ton per module. A methodology has been developed for the risk assessment of damaging debris impacts and for the design and testing of appropriate shielding. An innovative shielding concept has been developed at Alenia. The three-wall system is composed of a thin external layer made of aluminium spaced with an intermediate bumper made of a combination of ceramic fibres and high-strength fabric mixed with Epoxy resin; the internal wall made of aluminium alloy is the module structure to be protected. Hypervelocity experiments are performed using a light gas gun at the Ernst Mach Institute in Freiburg (Germany); aluminium spheres with a diameter from 0.9 to 1.75 cm are fired at velocities between 3 and 7 km/s. The experiments and the effectiveness of shielding are compared and evaluated with numerical simulations in collaboration with the University of Rome "La Sapienza". With these shields, the probability of perforation of the pressure shell of the European module has been reduced to less than 1.5 per cent over 10 years.

## 5. Effects of meteoroid streams on space platforms investigated by ground-based radars

23. Natural meteoroids are an important component of near Earth space environment and represent a potential risk for all Earth-orbiting space platforms; they significantly increase during enhanced (outburst or storm) activity of meteoroid streams, e.g. those related to the Leonids event, which occurs once a year. Their size is generally small (millimetre), but their velocities (up to 70 km/s) are very high; they can damage or erode satellite surfaces and external structures or cause electromagnetic shocks. Meteoroid flux predictions and investigations on their effect on penetration, charge production and plasma generation are relevant aspects for developing strategies for the safe deployment of the near Earth-orbiting space platforms.

24. Ground-based radars are a powerful tool for the observation of space objects, in particular those with all-weather and day-and-night performance. The CNR FISBAT Institute at Bologna has used a radar facility since 1992 to observe and measure the ionization cloud in the wake of a meteoroid. Impact probabilities of storm meteoroids on

space platforms in low-Earth orbit were calculated using the available data; it has been shown that the impact probability deduced by radar measurements is generally larger by a factor 2 than the one obtained by visual observations. Furthermore, radar data show that impact probability values of storm meteoroids can increase by factors of $10^2$-$10^4$ and more over the sporadic background.

### 6. Juridical work

25. At the University of Rome "La Sapienza" there is an active interest in studying governmental responsibility for activities in space; among them, at present, those arising from the production of debris is dominant. These responsibilities are void if the ownership of a spacecraft is not officially recognized, for example, through registration under the Convention on Registration of Objects launched into Outer Space. Italy has neither signed nor ratified it yet, but the Ministry for Foreign Affairs has begun steps to adhere to this important tool of international legislation of great importance for space debris.

## Japan

[Original: English]

### 1. Introduction

1. Japan has conducted a series of activities related to space debris in accordance with the Fundamental Policy of Japan's Space Activities issued by the Space Activities Commission of Japan in January 1996.1

2. Systematic and organized activities have been conducted since the Japan Society for Aeronautical and Space Sciences (JSASS) established the Space Debris Study Group in 1990. The National Aerospace Laboratory (NAL), the Institute of Space and Astronautical Science (ISAS), the National Space Development Agency (NASDA) of Japan and other space-related organizations (participating collectively as Japan) have been a consistent member of the Inter-Agency Space Debris Coordination Committee since 1992 and have also contributed to the Committee on Space Research, the Committee on the Peaceful Uses of Outer Space, the International Astronomical Federation and other international organizations.

3. The present report is a brief overview of the recent space debris activities in Japan regarding their measurement, database, protection and mitigation.

### 2. Measurement

4. ISAS and the Communication Research Laboratory have been conducting optical observation of space debris in low-altitude and geostationary orbits. ISAS and Kyoto University have been conducting radar observation in low Earth orbit. ISAS uses bistatic radar observation technology and Kyoto University uses very high frequency (VHF) middle and upper atmosphere radar (MU radar).[2,3,4]

5. In 1998, NAL, NASDA and the Japan Space Forum announced a new construction plan for a space debris radar and optical observation system.[5] This system will make it possible to observe space debris down to one metre in diameter (at an altitude of 600 km) and its construction is to be completed in 2003.

6. NAL and NASDA conducted post-flight surface analysis and evaluation of the Space Flyer Unit retrieved from space in 1995, which provides additional data on distribution of

space debris dust. An on-board dust collection experiment on the manipulator development facility aboard Space Shuttle flight STS-85 was performed in August 1997 in cooperation with the National Aeronautics and Space Administration of the United States of America. NASDA has analysed particles captured by the aero-gel installed in dust collection equipment.[6] As the flight time was not long enough, only a few particles were captured. A similar device is currently under development for the Japanese Experimental Module (JEM) to be attached to the International Space Station.[7]

7. From 1994 to 1997, NASDA and JSASS conducted a joint study on a new possible on-board debris observation system in order to monitor space objects down to 1 cm in size and presented a baseline specification of such a system as an international cooperative mission.[8]

### 3. Modelling and database

8. NASDA developed a space debris database known as the Space Debris Orbit Analysis Test System in 1997 and started its operation in April 1998. The objective of the database is to provide a tool for orbital data management and orbital data analysis of the resident objects. Several sub-functions, such as re-entry prediction, collision analysis and debris dispersion analysis are also provided for.

### 4. Protection

9. NAL and NASDA have conducted a series of studies and tests of a development system for the pressurized module of JEM. By 1998, NAL and NASDA had conducted a numerical analysis of high-velocity impact phenomena, simulated high-speed impact damage tests using a one-stage power gun, a two-stage light gas gun, a rail gun and a shaped charge system,[9,10,11,12] and reflected the data acquired by the analysis and tests into the design of the JEM flight model.

### 5. Mitigation

10. In order to minimize damage by space debris, NASDA established a Space Debris Mitigation Standard, NASDA-STD-18, in March 1996. NASDA is continuously making efforts to reduce the creation of new space debris by the study of safe controlled re-entry of expendable rocket bodies and spacecraft and of the related engineering criteria for ground hazard alleviation. In accordance with STD-18, NASDA has conducted the passivation and minimization of orbital life of upper rocket stages in order to mitigate the generation of space debris as a regular routine.[12,13]

### 6. Conclusion

11. As a responsible international partner, Japan has made every possible effort to cope with space debris issues and the management of the outer space environment. Japan will continue to pay utmost attention to those problems and believes that international cooperation is essential to ensure safe and long-lasting space activities by protecting the space environment from space debris.

*Notes*

[1] Fundamental Policy of Japan's Space Activities, Space Activities Commission of Japan, revised on 24 January 1996.

[2] T. Sato and I. Kimura, "Debris observation with a VHF radar", *Earth Science Review*, vol. 4, No. 3 (1995).

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Committee on the Peaceful
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# National research on space debris, safety of nuclear-powered satellites and problems of collisions of nuclear-powered sources with space debris

**Note by the Secretariat**

**Addendum**

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V.99-81326 (E)

# I. Introduction

1. The Secretary-General, in a note verbale dated 17 July 1998, invited all Member States to provide information on national research on space debris, safety of nuclear-powered satellites and problems of collisions of nuclear-powered sources with space debris.

2. The present document contains information provided in replies received from Member States between 30 January and 23 February 1999.

# II. Replies received from Member States*

## Germany

[Original: English]

1. Germany maintains a strong commitment to space debris research. The activities are either conducted on a national footing or are funded under contracts with the European Space Technology Research Centre and the European Space Operations Centre (ESOC) of the European Space Agency (ESA), which is financed through contributions of its member States, with Germany providing a share of around 25 per cent. These space debris-related activities in Germany are concentrated largely in the Institute of Flight Mechanics and Space Flight Technology of the Technical University of Braunschweig (IFR/TUBS) and the Research Establishment for Applied Science of Wachtberg-Werthhoven (FGAN). In addition, other research activities are also being carried out, for example, in the German space industry.

2. The following sections of the present report are accordingly structured and cover space debris-related research activities on modelling; radar observation and data analyses; and other space debris-related research activities.

3. The report describes activities carried out since the previous submission (see A/AC.105/680/Add.1 of 2 February 1998). During that period, the German Aerospace Centre (DLR) held a workshop on the review of the national space debris strategy on 22 October 1998. The main characteristics of this new strategy are:

(a) Coordination of the space debris-related activities of German industry and science as well as DLR's own activities;

(b) Formulation of an autonomous contribution for an integrated European space debris strategy in ESA, including the available entities in Germany;

(c) Development of capacity for the performance of risk analysis, where national interests are affected;

(d) Drawing up of proposals and recommendations for debris avoidance and mitigation;

(e) Design of monitoring methodologies for nationally or governmentally subsidized or financed space projects with regard to avoidance of debris generation as well as compliance with international requirements and regulations;

* The replies are reproduced in the form in which they were received.

(f) Collaboration of DLR in the formulation of international regulations and agreements, including representation of German interests on international committees (such as ESA Space Debris Coordination, the Inter-Agency Space Debris Coordination Committee (IADC) and the Committee on the Peaceful Uses of Outer Space.

4. The national strategy was presented at the annual meeting of IADC. A DLR-led delegation participated in the meeting, with five representatives coming from various institutions in Germany. An expert from FGAN currently chairs Working Group 1 (Measurements).

5. Germany strongly supports the activities in the Scientific and Technical and Legal Subcommittees of the Committee on the Peaceful Uses of Outer Space aimed at finalizing the work on the report containing the results of the multi-year work plan on space debris. The report should be adopted at the 1999 session of the Scientific and Technical Subcommittee in order to be presented at the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE III), to the intergovernmental conference as well as at the Technical Forum. The German delegation to UNISPACE III as well as the German experts attending the Technical Forum will be ready to contribute actively to the discussion of the report and to deliberations on the further discussion of the space debris issue in the Committee on the Peaceful Uses of Outer Space.

## 1. Space debris-related research activities on modelling

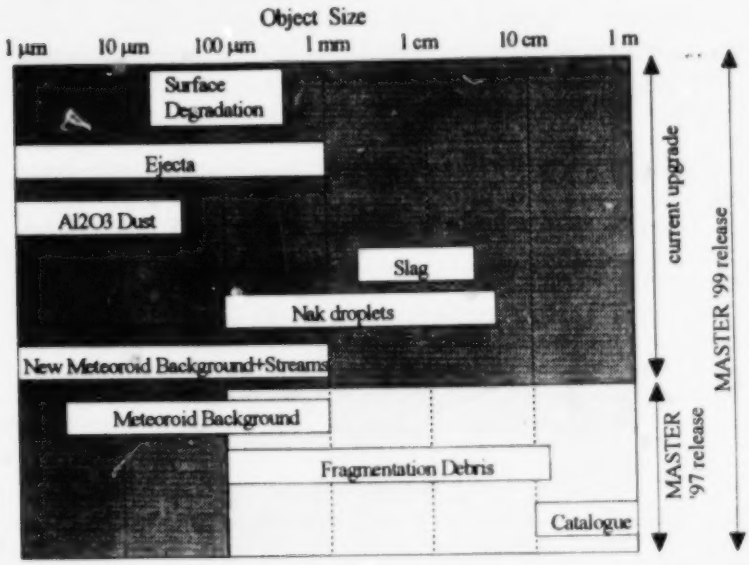
6. In 1998, IFR/TUBS worked mainly on two ongoing space debris-related studies for ESA. Both studies concentrate on the ESA Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) model.

### (a) Upgrade of the MASTER model

7. As pointed out in the previous submission (see A/AC.105/680/Add.1), the ESA MASTER[1] model is undergoing an upgrade concerning non-fragmentation debris down to 1 mm in size. That upgrade has become necessary owing to a number of measurements and observations that are indicating that man-made debris is not created exclusively by fragmentation processes. The larger residuals from solid rocket motor burns, the so-called "slag", as well as coolant droplets (sodium-potassium (NaK)) released from spent nuclear reactors[2] in space have been detected by ground-based radar facilities.[3] These objects are in a size range of larger than about 5 mm up to several centimetres in diameter. A major contribution from those sources can be expected according to the inclination spectrum of detected objects and related spatial densities. In the smaller size ranges, the smaller exhaust products from solid rocket motor burns, particles generated by surface degradation, as well as ejecta[4] resulting from small impacting primary objects are considered to contribute to the small-size man-made debris environment.

8. The background meteoroid branch of the MASTER model, which was originally based on the Divine/Staubach approach, has been redesigned and supplemented by a model for meteoroid streams.[5, 6] Figure 1 depicts the overall model improvements in terms of debris source and size range considered.

**Figure 1**
**Overview of the MASTER upgrade and the non-fragmentation debris sources considered**




9. According to the structure of the MASTER model, the non-fragmentation sources have been defined using a high spatial resolution from 200 km altitude (low Earth orbit (LEO)) up to the geosynchronous orbit (GEO) region. All sources have been treated semi-deterministically during the developing phase of the model. Individual objects have thus been generated. These are described by a set of orbital elements classified by epoch of generation and by mass and size. At the following stage of the process, all objects are extrapolated to a common epoch, the so-called "reference epoch". The model will be released officially in the last quarter of 1999.

10. A consequence of the MASTER extension is an increased complexity of the program and therefore also an increased demand for input data acquisition and for output data visualization. As a result, MASTER is currently migrating from a command line program to a state-of-the-art menu-driven application.

11. A graphical user interface is being developed that provides a nutshell for the MASTER binaries. The user will interact with this interface only and the MASTER binaries are executed in the background. The MASTER interface offers the following services (see the example in figure 2):

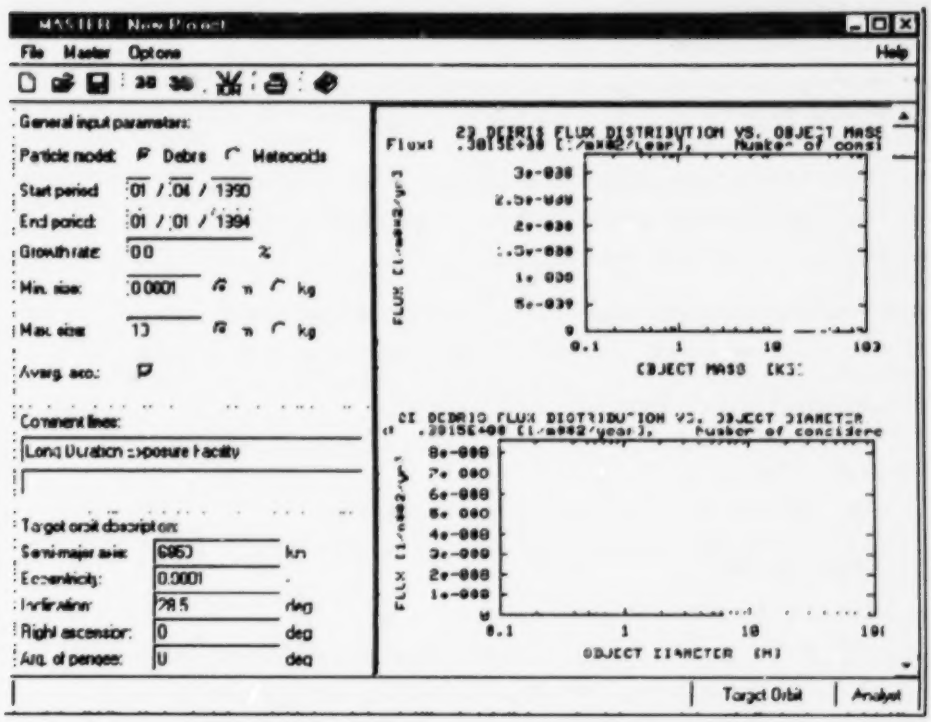
(a) Provision of an ergonomic and intuitive interface to pass all necessary input data to the MASTER applications;

(b) Execution of MASTER (analyst and engineering application);

(c) Display of graphical distributions of MASTER results either on screen or with postscript devices;

(d) Provision of on-line help to the user.

**Figure 2**
**MASTER graphical user interface**




**(b) Extension of the MASTER model to predict debris detections**

12. The main aim of the study is the development and implementation of a modular software tool for the prediction of crossing rates and statistical detection characteristics of objects below the United States Space Command (USSPACECOM) Satellite Catalog threshold and for the prediction of acquisition times and pass characteristics of deterministic Catalog objects. Predictions will be possible for both radar and optical observation systems with related system constraints, and also for both ground-based and space-based installations. Mathematical methods (for both statistical and deterministic analysis) lead to crossings or predicted acquisitions for a given sensor field of view (and range/range-rate windows in the case of radar systems). Based on the sensor-specific system performance model, the crossing rates are then translated into detection rates and detection size thresholds for a given probability level, assuming predefined shape, material and surface properties of the target objects.

13. The resulting software system, the Program for Radar and Optical Observation Forecasting (PROOF), is highly modular. It includes interfaces to the upgraded MASTER model population (for statistical analysis) and to a Catalog file at a certain date (for deterministic analysis, with data appearing in two-line format and as unique entries for each

object). The software system is capable of verifying individual contributions of the MASTER model population (e.g. NaK droplets) against existing measurement data (e.g. Haystack or COBEAM). The software is also able to assist in the planning of observation systems and campaigns.

14. The PROOF software considers:

(a) All known particulate sources with object diameters larger than 1 µm (the environment defined by the MASTER upgrade population, and by the USSPACECOM Catalog in the case of larger-size objects);

(b) Altitudes between 150 km (sub-LEO) and 38,000 km (super-GEO);

(c) Radar and optical systems, both ground-based and space-based;

and will be released officially in the last quarter of 1999.

## 2. Radar observation and data analyses of space debris and meteoroids

15. In 1998, space debris- and meteoroid-related activities at the FGAN Research Institute for High-Frequency Physics (FHP) were conducted mainly in the framework of three ESA/ESOC study contracts:

(a) Advanced radar techniques for space debris observation (February 1995-September 1998),

(b) Cooperative debris tracking (April 1997-July 1998);

(c) Development of algorithms for the detection of mid-size debris with radar (April 1997-July 1999).

16. The main objectives of these activities are:

(a) Investigation of improved debris observation and data collection techniques;

(b) Development and implementation of efficient, highly automated techniques and algorithms for data processing, debris and meteoroid detection and analysis;

(c) Support for establishing a unique, clearly defined interface between measurement results and modelling predictions.

### (a) Radar observation and data analyses of meteoroids

17. Sensitivity assessments revealed that the Tracking and Imaging Radar (TIRA) L-band radar is currently capable of detecting 2 cm spheres at 1,000 km range, using optimum detection strategies and taking into account all hardware and signal processing modifications and improvements proposed and implemented in the framework of ESA study contracts.[7, 8, 9]

18. The FGAN-FHP TIRA system is used primarily to investigate methods and techniques for classification and identification of spacecraft and aircraft. To a certain extent TIRA is also used to detect meteoroids, to observe their ionization trails and to determine their flux. These trails have a length of about 10 km and are located about 100 km above the ground. Knowledge of their flux is required to assess the risk of hazards to operational satellites by a major stream of activity of the Leonid meteor shower expected on 17 November 1999, for which the National Aeronautics and Space Administration (NASA) of the United States of America predicts an increase in the background flux by a factor of 10,000-30,000. A comparatively small flux of meteoroids is cut out from the

stream by the narrow beam of the TIRA antenna. Therefore even very small meteoroids, which are more numerous than larger ones, have to be detectable in order to achieve a statistically significant number of detections during the measurement time. An attempt to observe the Leonids in 1997 steering the antenna perpendicular to the stream failed.[10] Meteoroids as small as those required cause ionization trails of low electron density into which the incoming wave penetrates. Since the ionization trails have an initial radius of several wavelengths for TIRA, the waves reflected by the single electrons are cancelled to a large extent by interference.[11] This is why radars using a short wavelength like TIRA miss the required small meteoroids, even though a large reflector antenna of 34 m in diameter and high transmitted power of 1.5 MW is used.

19. In 1998, a major goal was to develop an alternative observing mode. This was conducted in the framework of the ESA/ESOC study contract for the development of algorithms for mid-size debris detection with radar (April 1997-July 1999).

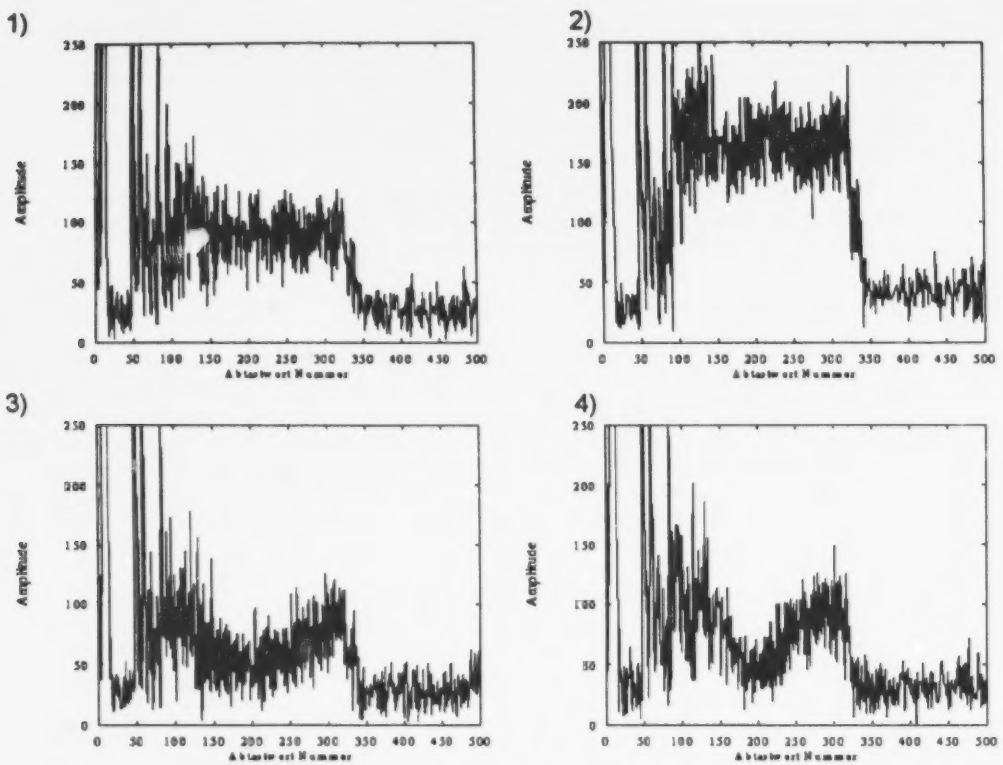
*(i) Observation of meteoroid flux*

20. As an alternative to looking perpendicular to the meteor stream, looking into the stream was investigated in 1998. Again, the antenna is steered to compensate for the rotation of the Earth. It was shown in theory[12] that particles producing an electron line density of $1.74.10^{12}$ $m^{-1}$, corresponding to a mass as small as approximately 3 µg, can be detected in a distance of 100 km, which suffices to produce a reasonable hourly rate cut out by the radar beam even though the cross section is smaller than in the perpendicular operation mode. The detection algorithms were further improved and automated.

*(ii) Measurement results*

21. Based on the bad experience gained from the Leonid observations in 1997, the theory of looking into the stream was tested by a measurement campaign for the predicted yearly maximum of the Perseid meteor shower conducted on 12 and 13 August for 15 hours. The number of detections agreed with the number predicted from the hourly rate measured by other observers and geometrical considerations and confirmed the theory. Encouraged by this result, researchers conducted a further measurement campaign for the Leonid meteor shower 17 and 18 November for about 12 hours. Because of the incorrect predictions of the time of maximum flux, the number of detections was lower than expected. Figure 3 shows 4 of the 5 last echoes contained in a detection of a total of 17 consecutive pulses from the Perseid measurement campaign. For each pulse the absolute values of the received signal samples are plotted over the sample number for a sampling interval of 2 µs. A pulse length of 500 µs and a pulse repetition time of 13.75 ms were used. Obviously, interferences occur slightly before vanishing.

**Figure 3**
**Radar echos of four consequent pulses**




**(b) Radar techniques for fragmentation and damage analysis of larger space debris**

22. The TIRA system has been used to assist in an analysis of the problem when unexpected events such as debris collision of an operational satellite causing fragmentation and damage have occurred. In the framework of study contracts, observations have been performed with the L-band and Ku-band imaging radar and the analysis results are being used to support the examination of the causes and amount of damage. Examples in 1998 included the observation and analysis of the Advanced Earth Observation Satellite (ADEOS), launched by the National Space Development Agency of Japan in 1996. With a budget of some US$ 1 billion, the satellite was designed for a lifespan of more than three years. Owing to a malfunction of the power supply system, however, ADEOS has been out of order since 30 June 1997.

23. Under the contract related to advanced radar techniques for space debris observation, ESA requested FGAN to measure and analyse several passages of ADEOS with its TIRA system. In order to examine the cause of the malfunction, a series of radar images with a resolution of 25 cm have been computed. Figures 4 and 5 give examples of computed radar images. Those images clearly show the main body of ADEOS with a dimension of

approximately 4 m x 4 m x 7 m. The mounted NASA scatterometer—a characteristic feature of ADEOS—is also visible. All the radar images also show a number of scatterers at the end of the boom of the solar panel. The solar panel has a length of 24 m, a width of 3 m and a thickness of only 0.5 mm. It was fixed to the boom by stiffeners made of carbon fibre, which should also be visible in the radar images. The lack of such scatterer centres in the images, together with the observed number of scatterers at the end of the boom, gave rise to the assumption that the solar panel was no longer fixed to the boom, but had shifted to its end. This assumption is supported by information from the National Space Development Agency (sensors on the solar panel recorded increases in temperature and vibration).

**Figure 4**
**Radar image of the Advanced Earth Observation Satellite**

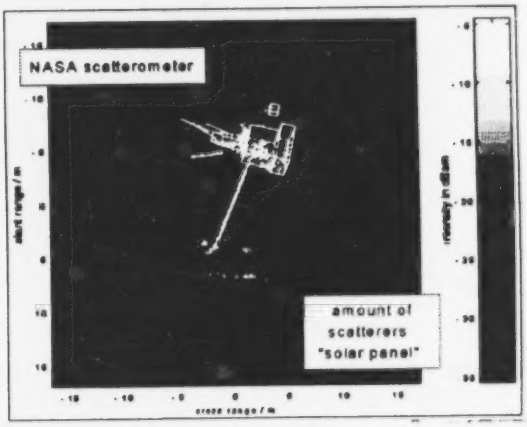
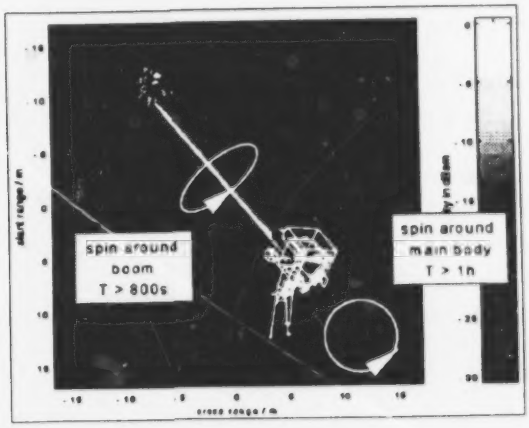



**Figure 5**
**Intrinsic motion of the Advanced Earth Observation Satellite**



24. To study the intrinsic motion of ADEOS, a simple three-dimensional wire-grid model was developed. It was found that ADEOS has a rotation period of more than 800 seconds around the boom and a rotation period of more than one hour around the main body.

**(c) Participation in the test campaign to verify the functionality of the Re-entry Database of the Inter-Agency Space Debris Coordination Committee**

25. Over recent years, FGAN developed radar techniques and analysis methods for re-entry observations of high-risk space objects. The objective was to provide the German Federal Ministry of the Interior with reliable predictions of re-entry windows (time and ground track), estimations of an object's altitude and risk assessments. FGAN (funded by a DLR contract) was thus well qualified to participate in the test campaign, whose main objective was to verify the functionality of the IADC Re-entry Database. The Re-entry Database was developed and implemented by GMV S.A. of Madrid under ESA contract. As a test object the German satellite Inspektor (object 25100) was selected. The satellite was observed worldwide and from optical and radar observations sets of orbital elements, the orbital lifetime and re-entry windows (time and location) were estimated and stored for comparison in the Re-entry Database.

26. From 27 October to 1 November 1998, FGAN performed a total of 20 radar observations of object 25100, computed sets of orbital elements and estimated orbital lifetime and re-entry windows. All results were stored in the Re-entry Database. On 1 November 1998 at 0906 Universal Coordinated Time (UTC), the very last measurement (the last visible orbit for the TIRA system) was conducted about 12 hours before decay. Using those data a re-entry window of 2138 ±2.1 hours was assessed. A post-analysis performed by ESA and NASA resulted in a re-entry window of 1949 ±2 hours.

**3. Other space debris-related research activities**

27. Some other space debris-related research activities under ESA contract in the reporting period, in addition to those mentioned above, were:

(a) The upgrade of the 1 m Zeiss telescope (Carl Zeiss, Jena) at the Teide Observatory in the Canary Islands, Spain;

(b) Advanced material models for hypervelocity impact simulations by the Ernst-Mach-Institut (EMI) in Freiburg to find out the dynamic parameters of various materials;

(c) Investigation of the phenomena of hypervelocity impacts on pressurized vessels (EMI);

(d) Studies by EMI of possible reinforcement of the impact shielding of highly exposed areas of the European Columbus Orbital Facility (COF)-module for the International Space Station;

(e) The upgrade of the ESA Database and Information System for the Characterization of Objects in Space (DISCOS) by eta_max in Braunschweig;

(f) Advanced models for spacecraft disintegration during re-entry by Hypersonic Technology Göttingen.

28. Besides these German activities carried out under ESA contracts, the nationally funded activities described below concentrate essentially on supporting risk analyses, studying degradation effects and contributing to IADC.

29. EMI is investigating the damage caused by the impact of micro-meteoroids and debris particles on coarse pointing mirrors of optical communication terminals in orbits with altitudes of 700 km and 1,400 km and an inclination of 48° E. For these orbits the maximum grade of damage was calculated as well as the probability of total destruction by the impact of a solitary particle.

30. At the Rheinisch-Westfälische Technische Hochschule in Aachen, several existing computer codes for risk analyses are undergoing benchmark testing. In addition, the establishment of a server to collect and distribute test results, computer programs and design formulas is in preparation. This work is a contribution to IADC Working Group 3 (Protection).

31. DLR has organized a national workshop to inform those involved in the field of space debris about the national strategy, near-term events (such as the re-entry of the Mir space station and the Leonid meteor showers), the status of work on the ESA Space Debris Mitigation Handbook, the work in the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space as well as in IADC. A representative of the reinsurer Bayerische Rück gave an overview of and background information on insurance and reinsurance in the space business.

32. Germany is a member of IADC and is represented by DLR, which contributes to the Coordinating Committee permanently in the form of exchange of information, preparation of activities in the working groups and coordination of the German delegation. DLR has taken the initiative to establish an IADC-homepage on the Internet. The German delegation to the 16th IADC Meeting, held in Toulouse from 3 to 6 November 1998, consisted of five delegates, one of whom now chairs Working Group 1 (Measurements). The DLR position paper on space debris, which describes the national strategy mentioned above, was also presented to the Meeting.

*Notes*

[1] J. Bendisch and others, "The consideration of non-fragmentation debris in the MASTER Model", paper presented at the forty-ninth Congress of the International Academy of Astronautics, held in Melbourne, Australia, in 1998 (IAA.6.3.04).

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[8] L. Leushacke, "First FGAN/MPIfR Cooperative Debris Observation Campaign: experiment outline and first results", *Proceedings of the Second European Conference on Space Debris, Darmstadt, Germany, 17-19 March 1997* (ESA SP-393).

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**Committee on the Peaceful Uses of Outer Space**

# Report on the Workshop on the Evaluation of the United Nations/Swedish International Development Agency International Training Course Series on Remote Sensing Education for Educators

## (Gaborone, Botswana, 18 to 21 October 1998)

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V.98-57878 (E)

# I. Introduction

## A. Background and objectives

1. The Workshop on the Evaluation of the United Nations/Swedish International Development Agency International Training Course Series on Remote Sensing Education for Educators, held in Gaborone, Botswana, from 18 to 21 October 1998, was organized by the United Nations Programme on Space Application in cooperation with the Government of Sweden. The idea to organize the workshop grew out of the recognition, based on evaluations carried out at the end of several of the United Nations international training courses on remote sensing education for educators (generally referred to as the United Nations/Sweden courses), that the needs of educators in remote sensing had evolved since the first course was held in 1990. It was therefore considered timely to assess how well the courses met current needs and to use the results of the assessment as a basis for proposing changes in course contents. The proposal to organize the workshop was made at the Seventh United Nations International Training Course on Remote Sensing Education for Educators held in 1997 (A/AC.105/678, para. 17).

2. The potential impact of the current course in spreading remote sensing education in developing countries can be compromised by a variety of local constraints. Consequently, the scope of the workshop was planned to include consideration not only of the contents and quality of the existing course relative to the on-the-job needs of educators but also of the full range of other factors that limit the efforts of educators at furthering remote sensing education. The principle objectives of the workshop were therefore to solicit feedback on the full spectrum of factors that impede remote sensing education and, on the basis of that feedback, to formulate recommendations and initiate appropriate actions to alleviate any existing difficulties. An additional objective was to provide a forum for the mutual exchange of experience on successful approaches to the development of remote sensing education. The workshop was co-sponsored by the Swedish International Development Agency (SIDA) on behalf of the Government of Sweden and was hosted by the Department of Physical Geography of Stockholm University and the Department of Environmental Science of the University of Botswana.

3. The present report describes the organization of the workshop, its recommendations and proposed follow-up actions. It has been prepared for the Committee on the Peaceful Uses of Outer Space and its Scientific and Technical Subcommittee.

## B. Organization and programme

4. Participation in the workshop was limited to graduates from African institutions since, based on feedback over the years, the region presented some of the more significant challenges to remote sensing education. Taking into account the assessment nature of the workshop, it was made open only to those graduates having at least two years of experience following the course in Sweden. Invitations were extended to all 78 graduates from African institutions who attended the course between 1990 and 1996. As a condition of their participation in the workshop, graduates were required to write a paper detailing their experiences at promoting remote sensing education, placing emphasis on the identification of factors that were critical to both their successes and failures.

5. Thirty-five graduates who submitted papers were retained as participants for the workshop; thirty-two were able to attend the workshop. They were nationals of the following 16 countries: Algeria, Burundi, Cameroon, Egypt, Ethiopia, Ghana, Guinea, Kenya, Lesotho, Nigeria, Senegal, Swaziland, Uganda, United Republic of Tanzania, Zambia and Zimbabwe. Funds for the international travel of five participants and their boarding and lodging were provided from the fellowship budget of the United Nations Programme on Space Applications. Funds for the international travel as well as boarding and lodging of the remaining 27 participants were provided by the Government of Sweden.

6. Workshop instructors and speakers came from several institutions, including the Office for Outer Space Affairs, the European Space Agency (ESA), Stockholm University, the University of Botswana and private industry.

7. The programme of the workshop was finalized following an analysis of the 35 papers. To ensure maximum interactivity and participation, the workshop was organized as a series of panel discussions in which each participant was assigned one or more formal roles as panellist and/or rapporteur. Each panel focused on a specific theme covering several related factors that the participants had identified in their papers as being critical to their successes or failures.

8. Panel discussions focused not only on gaining an understanding of the constraints hindering the development of remote sensing education but also on concrete proposals for alleviating such constraints. Proposals made at each panel discussion were compiled into a single list and workshop participants were required to grade the importance and relevance of each proposal in alleviating conditions within their particular local settings. This allowed ready identification of a limited number of priority proposals which, for the majority of participants, would be the most useful in furthering the local development of remote sensing education.

## II. Summary of the contents of the workshop

9. The first day of the workshop was reserved for technical presentations. These included presentations by invited speakers from Stockholm University, the University of Botswana, ESA and the Office for Outer Space Affairs. Oral presentations on the status of remote sensing education in several countries, as well as poster presentations on ongoing research activities were given by workshop participants. The second day included three panel discussions on the following themes: local development of remote sensing curricula; access to teaching and research materials; and professional development and trained staff. Presentations were also made by several workshop participants on the status of remote sensing education in their institutions and countries. On the third day, the panel discussions focused on the following: sharing of experiences; enlisting local support and funding; and strong points and shortcomings of the current course. Presentation, discussion and adoption of recommendations and proposals emanating from the panel discussions were carried out partly on the third and fourth days of the workshop. The greater part of the morning of the fourth day was spent visiting the remote sensing and geographic information system (GIS) laboratories of the University of Botswana, where participants had the opportunity to undertake computer-based hands-on exercises. The afternoon was spent on a field visit to a geological study area near the village of Manyana, several kilometres distant from the city of Gaborone.

## III. Recommendations

10. The problems enumerated and their proposed solutions, grouped into major categories according to the persons or entities proposed for initiating remedial actions, are presented in tables 1, 2 and 3. Implementation of the proposals in table 1 requires coordinated action on the part of graduates of the United Nations/Sweden training course, acting as a group. Proposals in table 2 require action on the part of national and international entities. Proposals in table 3 concern actions that are principally the responsibility of individuals, acting more or less independently.

11. In table 1, the major problems to be tackled by the participants themselves, acting as a group, relate mainly to the following: (a) insufficient access to information (e.g. on remote sensing developments, training opportunities, appropriate curriculum development); (b) insufficient access to satellite imagery; and (c) lack of political support. All participants considered those problems to be significant in their own work settings and graded the proposed solutions to be high in importance and applicability to their situations (from 65 to 94 per cent were graded in the "high" category). The proposals that they felt would alleviate present conditions call for the establishment of a formal association of educators of remote sensing in Africa and the creation of a Website.

12. Proposals for the solution of the major problems cited in table 2 require interventions by the parties currently involved in the organization of the present course in Sweden (Office for Outer Space Affairs, SIDA, Stockholm University and ESA). The problems are: (a) minor shortcomings of the present course, specifically with regard to the limited time allotted to curriculum development and to practical exercises; and (b) the general need for more opportunities for advanced training in remote sensing. The proposed solutions call for the course organizers to explore the possibility of enhancing those components of the present course that deal with curriculum development and practical exercises as well as to introduce a new advanced course in remote sensing. The recommendation addressed to ESA concerns the provision of opportunities to former graduates and others to acquire advanced knowledge in remote sensing and GIS techniques. This could be accomplished through a competitive arrangement that would allow interested educators to formulate project proposals and, if selected, to carry out a clearly defined work programme at ESA. Two recommendations addressed to

the Office for Outer Space Affairs, namely the establishment of a programme of assistance to provide educators with limited start-up funds and/or equipment and materials and the creation of regional centres of excellence in remote sensing, had already been acted upon before the workshop, although many participants were unaware of those activities owing to lack of access to information on them.

## IV. Proposed follow-up actions

13. The establishment of an association of remote sensing educators was considered to be of such high priority by the overwhelming majority of participants that they took the initial steps in its creation during the workshop. Actions taken included the election of several regional councillors who would contribute to the development of the statutes of the association and plan its initial activities (as an initial event, a technical workshop is planned to take place by the end of 1999). In addition, each participant made a financial contribution to cover the miscellaneous office expenses of the councillors. The Office for Outer Space Affairs plans to play an active role in supporting the future activities of the association. In particular, it will provide a sub-Website at its Internet address (www.un.or.at/oosa) in order to meet the specific needs identified earlier in the present report (see table 2).

14. The Office for Outer Space Affairs will undertake discussions with the various entities mentioned in the recommendations contained in table 2 (SIDA, Stockholm University, ESA, United Nations Development Programme (UNDP) with a view to facilitating and implementing the proposed solutions within a reasonable time-frame. Stockholm University has since reported that it has implemented several changes in the planned programme of the 1999 Ninth United Nations International Training Course on Remote Sensing Education for Educators, in conformity with the conclusions of the workshop. The changes include placing more emphasis on curriculum development and including more practical exercises, particularly those related to GIS and digital image processing. In addition, the set of teaching materials given to participants will be enhanced to include, among others, multiple copies of printed satellite images.

15. Initial discussions between the representatives of the Office for Outer Space Affairs and ESA at the workshop revealed that educators selected for ESA fellowships would be able to extract the greatest benefit from ESA laboratory facilities and available technical expertise if the award of fellowships were made conditional on the preparation of technically sound, well-reasoned project proposals. Under such an arrangement, selected educators would be required, during a first phase, to collect all locally available project materials while still at their home institutions and to initiate appropriate contacts with ESA laboratories in order to refine their subsequent work programme. The second phase would be a six-month period of study at ESA facilities, during which the emphasis would be on carrying out the pre-defined analytical and processing components of the work programme which, for a variety of reasons (e.g. lack of access to equipment or images), could not be undertaken at the educators' home institutions. The final phase would consist of preparation of a final project report by fellowship holders on their return home. The Office for Outer Space Affairs will continue discussions in 1999 with ESA on the details of implementation of the fellowship programme.

16. The Office for Outer Space Affairs will also specifically explore with SIDA and Stockholm University how the outcome of the workshop could be used to benefit graduates of the course from geographic regions other than Africa.

17. In view of the many local obstacles noted by educators of remote sensing in Africa and the lack of understanding or awareness by the public and decision makers of a technology that has significant impact on social and economic development, the Office for Outer Space Affairs has proposed the implementation of a high-level programme of awareness building on a country-by-country basis. As presently envisaged, representatives of the Office for Outer Space Affairs and SIDA will visit selected countries in Africa and meet with high-ranking officials from the Government and universities to discuss ways in which many of the local obstacles could be overcome in order to put to good use the value of the training received from the Government of Sweden. The proposal will be discussed with SIDA in 1999.

18. The proceedings of the workshop will be published and distributed by Stockholm University in collaboration with the Office for Outer Space Affairs. Volume II of the proceedings, which consists of a compilation of all papers submitted, was made available to participants at the beginning of the workshop. Volume I will contain the introductory papers presented on the opening day of the workshop as well as a summary of its recommendations and proposed follow-up plans.

Table 1
**Recommendations to participants of the Workshop acting as a group**

| *Major problem* | *Recommendation* | *Grading*[1] | | | |
|---|---|---|---|---|---|
| | | *H* | *M* | *L* | *X* |
| Insufficient access to satellite imagery for teaching and research purposes | Create an association of remote sensing educators and subsequently lobby space agencies (e.g. ESA) and other providers of satellite data for preferential access to satellite imagery for educational and research purposes in Africa | 29 | 1 | 1 | 0 |
| Insufficient networking, cooperation and collaboration | Create an association of remote sensing educators | 27 | 3 | 1 | 0 |
| Lack of reliable and efficient access to information on remote sensing developments | Publish a bi-annual to annual newsletter (via e-mail or regular mail, as necessary) | 20 | 7 | 4 | 0 |
| | Create an association of remote sensing educators to facilitate information access | 26 | 4 | 1 | 0 |
| Lack of political support | Create an association of remote sensing educators to lobby for support | 21 | 6 | 4 | 0 |
| Limited access to information on training opportunities to address problems of insufficient skilled manpower | Establish a Website to provide relevant information (with the assistance of the Office for Outer Space Affairs) | 21 | 8 | 2 | 0 |
| Insufficient access to information on the development of appropriate curricula for remote sensing and GIS | Establish a Website to provide relevant information (with the assistance of the Office for Outer Space Affairs and Stockholm University) | 23 | 5 | 3 | 0 |

[1] H, M and L denote high, medium and low gradings, respectively. Gradings reflect participants' evaluations of the importance and applicability of the proposed solutions in alleviating given problems within their own settings. X denotes cases where participants considered that a given problem did not exist or was considered insignificant within or irrelevant to their own settings.

Table 2
**Recommendations to third parties**

| *Major problem* | *Recommendation (specified third parties)* | *Grading*[1] | | | |
|---|---|---|---|---|---|
| | | *H* | *M* | *L* | *X* |
| Insufficient access to information on the development of appropriate curricula for remote sensing and GIS | Enhance the curriculum development component of the United Nations/Sweden course (Office for Outer Space Affairs/SIDA) | 13 | 17 | 1 | 0 |
| Insufficient personnel skilled in remote sensing | Organization of an additional short course on remote sensing to fulfil the demand (Office for Outer Space Affairs/SIDA) | 18 | 12 | 1 | 0 |
| | Allow technicians (who assist teachers) to participate in the existing course (Office for Outer Space Affairs/SIDA) | 10 | 16 | 5 | 0 |
| Insufficient access to regional remote sensing centres of excellence | Establish centrally placed subregional remote sensing centres to cater for all users (Office for Outer Space Affairs/SIDA) (Morocco and Nigeria now host regional centres) | 18 | 9 | 3 | 1 |
| Shortcomings of the current content of the United Nations/Sweden course | Increase the time devoted to the theoretical and practical aspects of GIS (Office for Outer Space Affairs/SIDA) | 25 | 5 | 1 | 0 |
| | Provide a separate advance course and/or opportunities for more advanced training in remote sensing (Office for Outer Space Affairs/SIDA/ESA) | 18 | 9 | 4 | 0 |
| Disadvantages of having Sweden as the location of the United Nations/Sweden course (e.g. lack of similar facilities at home institutions) | Retain the course location in Sweden; benefits outweigh the disadvantages (SIDA/Office for Outer Space Affairs) | 24 | 6 | 1 | 0 |

| *Major problem* | *Recommendation (specified third parties)* | *Grading*[1] | | | |
|---|---|---|---|---|---|
| | | *H* | *M* | *L* | *X* |
| Insufficient funding/ sponsorship | Provide appropriate opportunities for educators to undertake advanced project-based studies in remote sensing (ESA) | 25 | 6 | 0 | 0 |
| | Provide opportunities for educators to obtain limited start-up funds and/or equipment and materials (Office for Outer Space Affairs, UNDP) | 21 | 10 | 0 | 0 |

[1] H, M and L denote high, medium and low gradings, respectively. Gradings reflect participants' evaluations of the importance and applicability of the proposed solutions in alleviating given problems within their own settings. X denotes cases where participants considered that a given problem did not exist or was considered insignificant within or irrelevant to their own settings.

Table 3
**Recommendations to individuals acting independently within their own settings**

| *Major problem* | *Recommendations* | *Grading*[1] | | | |
|---|---|---|---|---|---|
| | | *H* | *M* | *L* | *X* |
| Inadequate infrastructure (e.g. library/laboratory space) | Create a centralized facility at institutions (with unbiased leadership) | 13 | 11 | 5 | 2 |
| Lack of literature (e.g. books and journals) and equipment (e.g. computer hardware and software; equipment for cartography and for fieldwork) | Acquire through self-initiative (e.g. linkages, collaboration) and through appropriate organizations (e.g. United Nations, UNDP, ESA) | 20 | 11 | 0 | 0 |
| | Explore existing possibilities in each country (e.g. institutions, research funds) | 19 | 9 | 3 | 0 |
| Lack of efficient and reliable communication | Make efforts to get connected to the Internet | 13 | 10 | 6 | 2 |
| | Solicit newsletters from various remote sensing organizations (e.g. ESA, Swedish Space Corporation) | 16 | 14 | 1 | 0 |
| Insufficient networking, cooperation and collaboration | Institutions should draw up memoranda of understanding (e.g. to share materials and to pursue collaborative research) | 13 | 15 | 3 | 0 |
| Insufficient funding/ sponsorship | Obtain funds from national Governments, non-governmental organizations, and private individuals through projects/ consultancies that include a training component | 14 | 13 | 3 | 1 |
| | Improve, through appropriately linked programmes, programmes with other universities | 15 | 12 | 3 | 1 |
| Lack of awareness among the public and among decision makers | Create interest in remote sensing from the grass-roots level upwards (include decision makers) through workshops, seminars, dissemination of research results and informal relationships, as well as through the use of teachers and other professionals | 22 | 9 | 0 | 0 |

| *Major problem* | *Recommendations* | *Grading*[1] | | | |
|---|---|---|---|---|---|
| | | *H* | *M* | *L* | *X* |
| | Encourage the private sector to be involved in remote sensing projects that include students working on attachment | 23 | 5 | 3 | 0 |
| Lack of political support | Participants to be more proactive in soliciting support by acting in an advisory capacity to local governments | 13 | 15 | 3 | 0 |
| Insufficient time to carry out research activities in remote sensing | Lobby institutions to rationalize teaching and administrative loads to facilitate research | 7 | 15 | 5 | 4 |
| Diversion of research funds for uses other than the intended purposes | Lobby institutions to use research grants for the specified purposes | 10 | 11 | 5 | 5 |

[1] H, M and L denote high, medium and low gradings, respectively. Gradings reflect participants' evaluations of the importance and applicability of the proposed solutions in alleviating given problems within their own settings. X denotes cases where participants considered that a given problem did not exist or was considered insignificant within or irrelevant to their own settings.